

WISP: A Passively Powered UHF RFID Tag with Sensing and Computation

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Abstract

WISP is a wireless, battery-free platform for sensing and computation that is powered and read by a standards-compliant Ultra-High Frequency (UHF) RFID reader. The notable features of the device are a wireless power supply, UHF backscatter communication, and a fully programmable

ultra-low-power 16-bit flash microcontroller with analog to digital converter. We have implemented UHF-RFID powered-and-read light sensor, temperature sensor, accelerometer, and strain gage. We believe these are the first reported UHF powered accelerometers and strain gages. We have also implemented the RC5 algorithm on WISP, which we believe is the first strong cryptographic algorithm to be implemented on a UHF RFID tag.

Introduction: Ubiquitous Sensing

This chapter describes WISP (Wireless Identification and Sensing Platform), a wireless, battery-free platform for sensing and computation that is powered and read by a standards-compliant Ultra-High Frequency (UHF) RFID reader. WISP features a wireless power supply, bidirectional UHF communication with backscatter uplink, and a fully programmable ultra-low-power 16-bit flash microcontroller with analog to digital converter. This particular point in the sensor platform design space offers some attractive features for ubiquitous sensing, but has not yet been explored very thoroughly. Using the WISP platform, we have implemented the first accelerometer to be powered and read wirelessly in the UHF band, and also the first UHF powered-and-read strain gage. Even without its sensing capabilities, WISP can also be used as an open and programmable RFID tag: with collaborators we implemented the RC5 encryption algorithm on WISP[17], which we believe is the first implementation of a strong cryptographic algorithm on a UHF tag.

One approach to ubiquitous sensing is to use wired sensors. This approach is well-suited to creating purpose-built instrumented environments supporting long-term observation.[1] This approach has the advantage that there is no battery lifetime or battery size constraint. The

drawback is the need for wires. In [1], the authors describe such a purpose-built living space, which includes custom cabinetry to house sensors as well as cables for both power and data. A second approach, favored by the Wireless Sensor Networks community, is to use battery-powered devices that communicate by ordinary radio communication, often in a peer-to-peer fashion.[2] One disadvantage of this approach is the size and lifetime constraints imposed by batteries. Because of the lifetime constraint, it would not be possible to permanently embed a battery-powered device in a building or civil structure such as a bridge. A third approach includes generating power from environmental sources[3], such as vibration, light, or human motion,[4] and then communicating the sensor data by ordinary RF transmission. The final class of approaches, within which this work fits, is to deliberately transmit power from a large source device to the sensor platforms, which then harvest this “planted” power, rather than relying on generation of electrical energy from naturally occurring or “wild” sources as in the third approach.

The space of wireless power/data transmission can be subdivided further. Chip-less approaches such as Theremin’s cavity resonator microphone[5], as well as more recent examples such as [6] and [7], are based on an analog technique in which a quantity to be sensed modifies the frequency or quality factor of a resonant structure. Changes in the resonance can be detected by a “reader” device that is effectively supplying power and collecting analog sensor data. This analog approach is generally limited to a small number of sensors, since the devices cannot be given arbitrarily long unique IDs. Furthermore, these analog sensor devices are not capable of on-board computation, which means the system cannot benefit from channel sharing, error detection and correction, embedded compression and filtering, cryptography, and other

capabilities enabled by digital computation and communication.

RFID tags are wirelessly powered digital devices that include a conventional Integrated Circuit (IC).[8] Conventional RFID tags are fixed function devices that typically use a minimal, non-programmable state machine to report a hard-coded ID when energized by a reader. The Electronic Product Code (EPC) standard operates in the Ultra-High Frequency (UHF) band (915MHz in the U.S.), which has substantially improved the range and field-of-view for RFID reading over previous generations of RFID technology. The “EPC Class 1 Generation 1” specification [9] (“Gen1”) was the first UHF RFID standard to be widely deployed. The standard’s broad adoption enabled a new generation of applications and interoperable products. This standard has been supplanted by the a second generation spec of the specification, “EPC Class 1 Generation 2.”[10] As of this writing, WISP supports the Gen 1 but not the Gen 2 specification, although we are developing a Gen 2 WISP.

RFID has been used for sensing in several contexts. Conventional short range HF RFID tags with a worn RFID reader have been used for activity monitoring in eldercare scenarios[15]; in this case, the RFID read event is in effect a reader-tag proximity sensor. Integrating RFID tags with secondary sensors has been proposed [11] or implemented [12] in various contexts, and a small number of commercially available RFID sensors exist. In almost all cases, these devices are fixed-function, and simply report a unique ID and sensor data. Most of the commercially available products are “active tags,” meaning that the sensor platform is battery-powered; they use the RFID channel for communication but not power. Also, existing RFID-sensor devices are generally not programmable platforms supporting arbitrary computation. Most recent research in

IC-based passive sensor tags has proceeded incrementally to augment the capabilities of RFID tags by integrating additional functional blocks without going beyond a simple digital state machine at the core. Thus these devices are, like ordinary ID-only tags, fixed in function, not programmable. For example, ADCs, specialized logic, and temperature sensors have been integrated into tag ICs with a finite state machine architecture typical of RFID tags [13,14]. WISP represents an alternative design philosophy that focuses on the programmability of a full microcontroller as part of a sensor-enhanced, passive RFID device.

One commercially available fully programmable microcontroller with an RFID interface is described in [15]. However, this device can only transmit one bit of sensor data per read event, and operates at 125kHz, which limits its range to inches. The Near Field Communication (NFC) standard is also a relevant point of comparison[16]. NFC uses short-range RFID-style 13.56MHz communication to link powered devices. It does not provide any power harvesting capability.

The general-purpose WISPs that are the focus of this chapter were preceded by several less capable devices (also called WISPs) that were described in previous publications. The α -WISP [17] used two mercury switches to mechanically toggle between two commercially produced RFID integrated circuits (IC). Thus if either of the two IDs was detected, it is interpreted as indicating object presence; which of the two IDs is read effectively conveys one bit of sensor data. We refer to this technique as ID Modulation. The π -WISP [18] 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, to implement an electronically controlled

form of “ID Modulation.”[19] The π -WISP could transmit at most one bit of sensor data per query, and used two separate antennae for communication and power harvesting. In [20], we presented the first WISP to implement the Gen 1 protocol on its own, without using a commercial RFID tag. This was the first WISP to use a single antenna for power harvesting, reader-to-WISP data downlink, and WISP-to-reader data uplink. Like its predecessors, this WISP also encoded the sensor data in the EPC ID, but was able to control all bits of the ID, unlike the earlier ID Modulation devices. We reported light level measurement using this platform; it also used its on-board processor to compute the CRC of the live light level data [20]. In [21], we described a next generation of the WISP hardware (known as Rev I), and presented a more detailed discussion of its design. The Rev I WISP used a demodulation technique based on a “mini-harvester.” This chapter focuses on a next generation of WISP (called Rev 2.3) that is smaller than its predecessors and uses a new demodulator called the “multifunction harvester-demodulator” that reduces demodulator current leakage thus yielding improved range. Fig. 1 is a photograph of the Rev I and Rev 2.3 WISPs. Instead of a demodulator based on a second parallel harvester (as in the Rev I WISP), the Rev 2.3 WISP’s main harvester can be selectively placed in a demodulation mode; when demodulation is not enabled, there is no power leakage through the demodulator.

The remaining sections of this chapter present the WISP design and power budget, followed by experimental results on range, and several representative applications, including several sensors and the RC5 cryptographic algorithm.

WISP Design

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 Rev I WISP pictured in Fig. 1 is made of a two layer FR4 PCB with components limited to the top side. The Rev 2.3 board, also pictured, has components on both sides. A dipole antenna made of solid core wire is visible. The Rev 2.3 WISP in its base configuration (with no sensor daughterboard) has two onboard sensors: a temperature sensor and an accelerometer.

Small header pins expose microcontroller ports for expansion daughter boards, external sensors and peripherals.

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 $4W_{\text{EIRP}}$ (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.

Demodulation and Modulation

To encode reader-to-WISP data, in the EPC Gen 1 standard 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.” The harvester effectively demodulates the 915MHz carrier, and leaves a baseband data signal---the downlink data---on the order of 70kHz. Most of this signal is rectified into a DC voltage by the top right diode and large charge storage capacitor. When the demodulator is enabled, some of the signal travels through the demodulator branch. This signal is also rectified, to produce a reference voltage for the bit detector, but the filter capacitor after the demodulator diode is much smaller than the power accumulator capacitor . Effectively it removes the 70kHz data signal and leaves 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. Using this dynamic threshold, the instantaneous output voltage from the voltage doubling ladder is thresholded by a Schmitt trigger inverter, which removes 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-capacitor pair in the demodulator section. Note also that because the final diodes are 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.

Uplink

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 ideally has no effect on the antenna, and thus the power harvesting and data downlink functions occur as if it were not present. WISP accomplishes this impedance modulation with a 5GHz RF bipolar junction transistor which allows for effective shunting of the 915MHz carrier wave.

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, we have shown that it is now possible to construct working, passively powered RFID tags with discreet components.

Most importantly, the general purpose computation abilities of WISP are enabled by an ultra low power microcontroller. The 16-bit flash microcontroller used in the Rev I WISP, the MSP430F1232, 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 [20]; in [21], we extended the range over the early results of [20] 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. The Rev I 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.

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.

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.

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.

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.

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.

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 than 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.

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.

As shown in [21], the Rev I WISP requires at least -4dBm or -0.5dBm to function, depending on whether the power available to the WISP has dropped from a higher level (in which case it can function all the way down to -4dBm) or is rising from below (in which case it will not start until it has reached nearly -0.5dBm). (In the latter case, “start up” energy costs as well as component brown-outs increase the device’s effective power requirement.) Using these best- and worst-case input power figures, 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, λ 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 $P_T = 1\text{W} = 30\text{dBm}$. Its center frequency is 915MHz, corresponding to wavelength $\lambda=0.33\text{m}$. The transmit antenna gain $G_T = 6\text{ dBi}$ (this yields an

effective isotropic radiated power of approximately $4W_{\text{EIRP}}$, 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, 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 later sections.

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 $600\mu\text{A}$ at 1.8v. Only the WISP's active period is considered, which is measured from first bit of the received preamble to $100\mu\text{s}$ after the last bit of the response packet is transmitted, totaling 2ms. For a storage capacitor of $8.5\mu\text{F}$ voltage head room needed 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.

$$V_{dd} (I_s + I_w) T \leq \frac{1}{2} C (V_{rec}^2 - V_{dd}^2) \quad (2)$$

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 $\frac{1}{2} CV_{rec}^2$, but not all of it is usable since charge stored on the capacitor at a voltage less than 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.

Experimental Results

Fig. 6 shows experimental results of the WISP performance, plotting harvested voltage output as a function of range from an RFID reader, for the Rev I and Rev 2.3 WISPs. 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 antenna was then moved away from the WISP 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.)

This data shows the mean voltage for a Rev I and for a Rev 2.3 WISP 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 almost 4 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 3m (where the voltage is lower), and indeed experimental observation is consistent with this expectation.

The non-monotonic behavior of the rectified voltage is believed to be a multipath effect. We have seen qualitatively similar non-monotonicity in [17], [20], and [21], and Fig. 3 of [22] 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.

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. Figure 7 shows results from a light level measurement made with WISP[20].

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. Figure 8 shows a time series of temperature measurements reported by WISP using an external temperature sensor. An inverted can of compressed air was used to generate a low temperature impulse. After the WISP's temperature sensor had recovered for about 30s, a heat gun was used to generate a high temperature impulse. The WISP continued to function properly even as its temperature sensor was driven from -40 degrees C to +60 degrees C.

Figure 9 shows data collected by a tri-axial accelerometer on WISP.[23] The accelerometer that draws 200uA at 1.8V. Due to the relatively high current consumption of these devices, continuously powering them would cripple the range of WISP. To overcome these high power requirements, the sensor is only be powered for a short period of time to take a measurement. Provided that the sensor and conditioning electronics can stabilize sufficiently quickly, this allows for a wide range of sensors to be measured over UHF RFID. Powering this accelerometer, the WISP is able to provide accelerometer measurements at rates of approximately 10 to 20 samples per second, depending on range. After the measurement is taken

and the data packed into the EPC ID, the WISP calculates the correct CRC. Then the “ID” is reported to the RFID reader, and the information is then decoded in real time by the computer.

Figure 10 shows a WISP strain gage device, compared to wired version of the same transducer, and compared to a more accurate extensometer device for ground truth measurement.[24] The power requirements of the strain gage are more substantial than those of the accelerometer: the strain gage is a relatively high current consumption resistive sensor, configured with a Wheatstone bridge and amplification.

Figure 11 illustrates an application that makes use of WISP’s computing rather than its sensing capabilities. With colleagues, we implemented the RC5 encryption algorithm on the WISP platform.[25] Most previous work on cryptography for UHF RFID assumed that sufficient power for “full blown” cryptography would not be available on a UHF tag. Therefore, many stripped down (or “minimalist”) cryptographic schemes have been proposed for UHF RFID. Unfortunately many have been broken. WISP shows that full blown or “maximalist” cryptography can be implemented on a UHF RFID tag.

Conclusion

This chapter presented the design of WISP, a programmable, passively powered UHF RFID tag. WISP includes a general purpose 16 bit flash microcontroller, with analog to digital converter. WISP is powered and read by an ordinary, unmodified standards-compliant UHF RFID reader. After presenting the design, power budget, and power harvesting performance of WISP, we described several applications: measurement of light, temperature, acceleration, and strain, as

well as implementation of the RC5 cryptographic algorithm.

More generally, 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.

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Figures

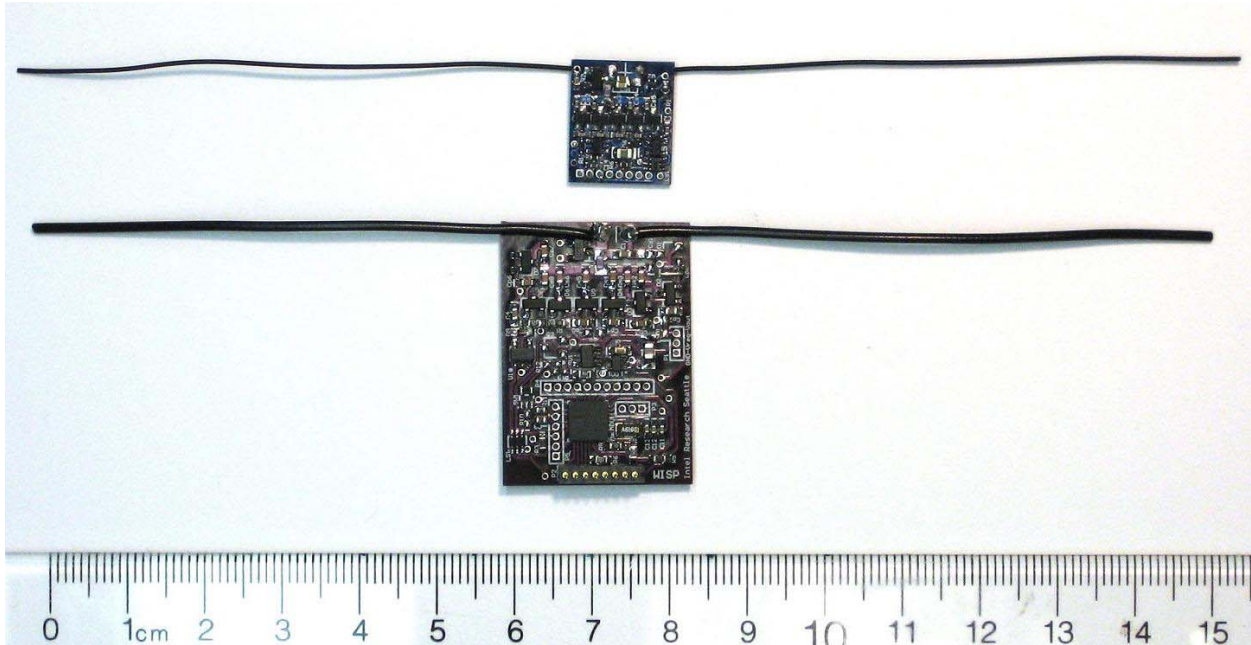


Fig.1 Photograph of WISP (Rev 2.3, at top) and an older WISP (Rev I, below), with a ruler for scale. The design was shrunk by using both sides of the PCB, using smaller components, and eliminating headers. Both boards include an accelerometer and an external temperature sensor (in addition to one built in to the microcontroller). Additional sensors or LEDs can be added by attaching a daughter board to header pins on the WISP.

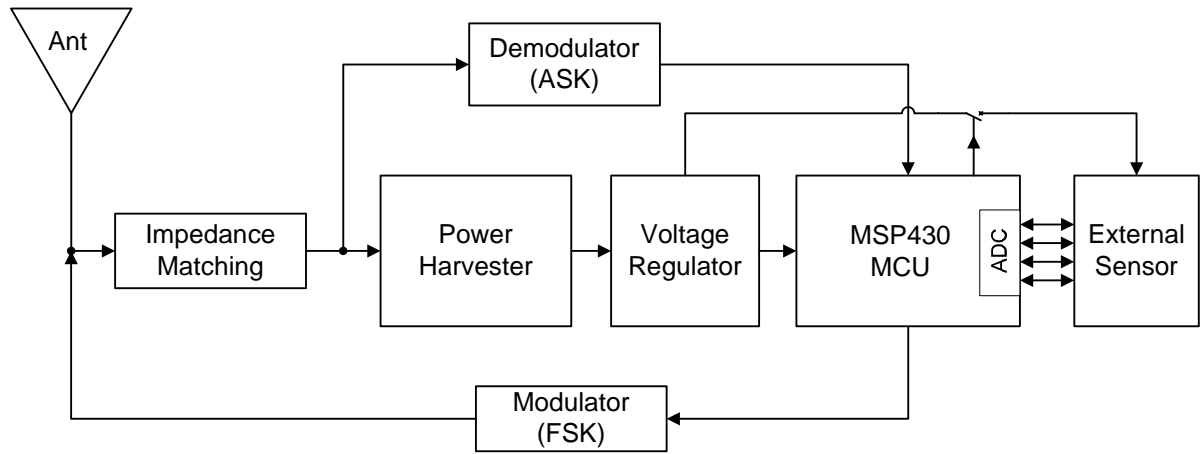


Fig. 2 Block Diagram of the WISP platform. (From [21]. With permission.)

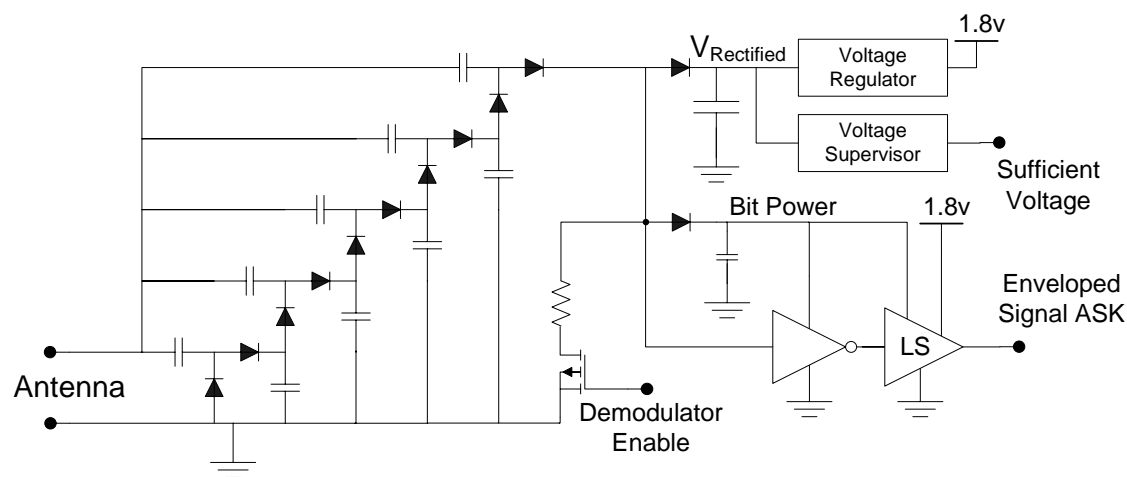


Fig. 3. Schematic of Rev 2.3 WISP. This design improves on the mini harvester of the Rev I WISP described in [21]. The two rightmost diodes are low frequency, low leakage diodes. The 10 diodes in the voltage doubling ladder are RF Schottky diodes. Instead of using a second mini-harvester for demodulation, the demodulator is connected directly to the main harvester, but can be disabled to prevent energy from leaking through the demodulator's pull-down resistor. The component labeled “LS” is a level shifter.

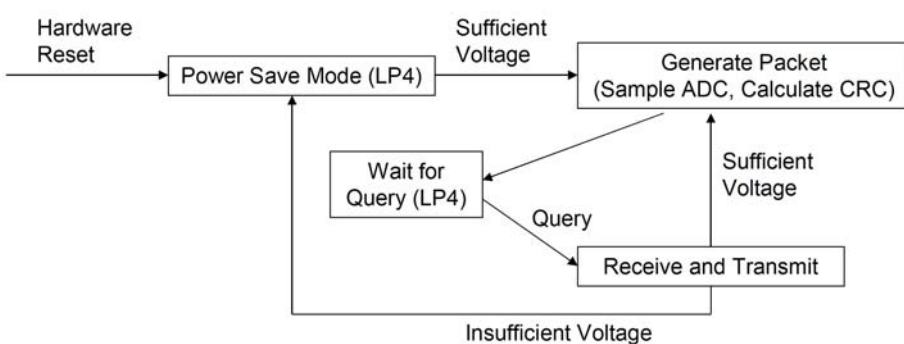


Figure 4. Operational power cycle. The hardware reset occurs at a lower voltage threshold; the “sufficient voltage” threshold is higher than the hardware reset threshold. When the voltage is between the lower and upper thresholds, the WISP remains in Power Save Mode, which retains

state. (From [21]. With Permission.)

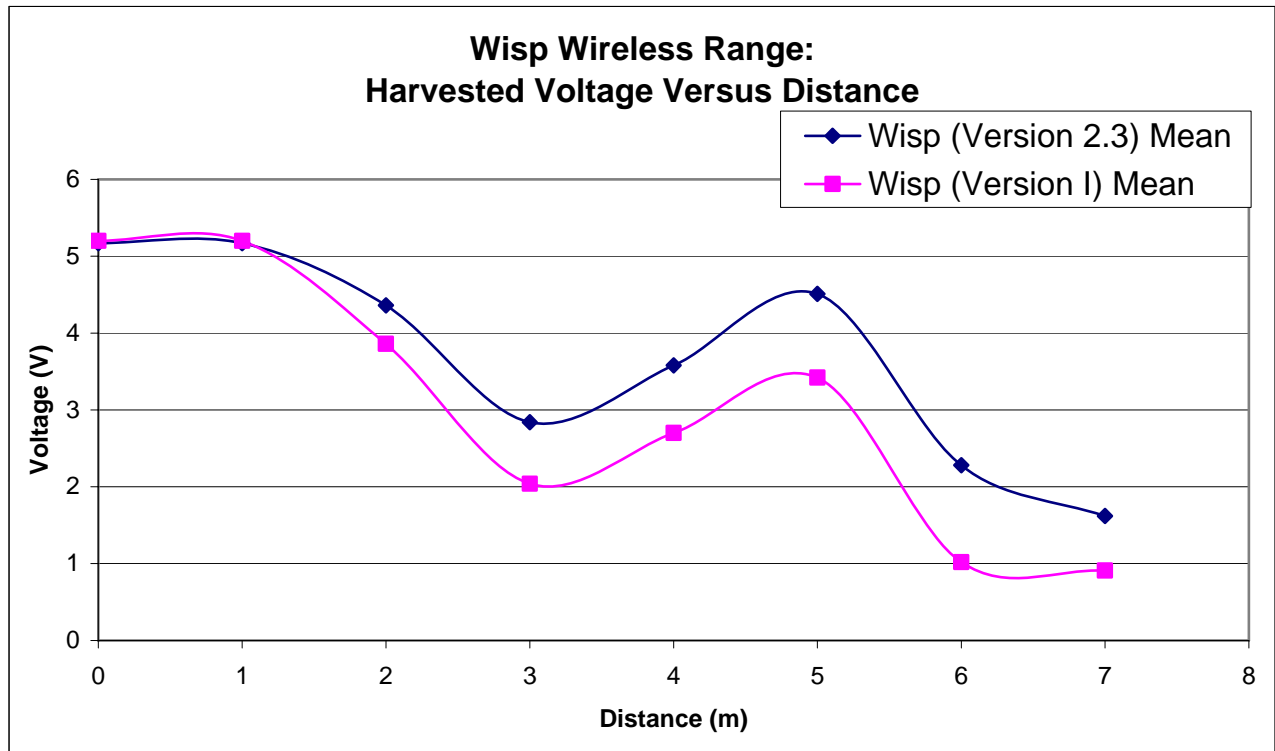


Figure 6. Rectified voltage in sleep mode vs. distance for the Rev I and Rev 2.3 WISPs. These data were generated with the reader set to produce blocks of 30 queries.

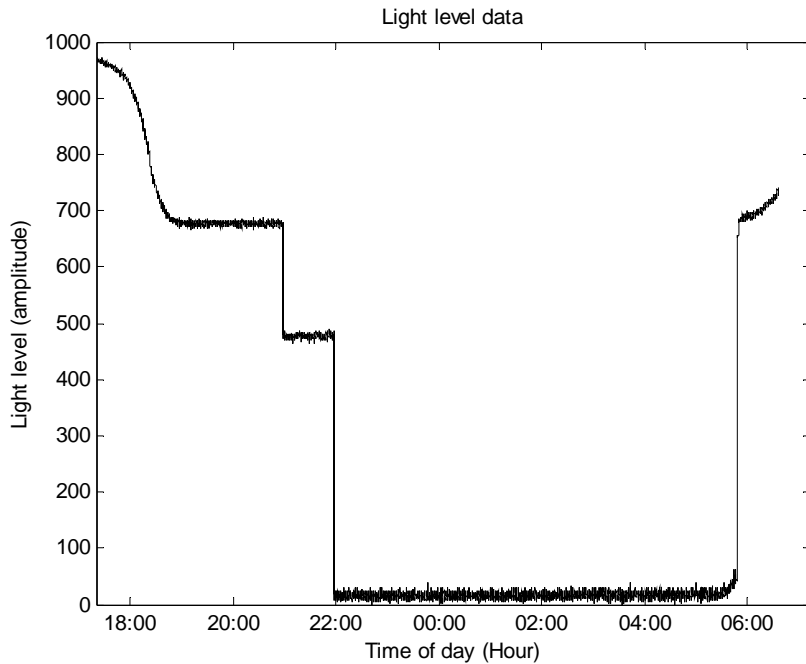


Figure 7. Light level measured by WISP in a 13 hour period. The experiment began at about 5:40pm (17:40 hours). The first curve down is sunset. At around 9pm (21:00 hours), the measured light level drops substantially, probably because some lights in the laboratory were extinguished. At about 10pm (22:00 hours), the light level drops very low, probably because the remainder of the lights in the laboratory were extinguished. Just before 6am (06:00 hours), the beginning of sunrise is visible, and the laboratory lights turn on. [From 20. With Permission.]

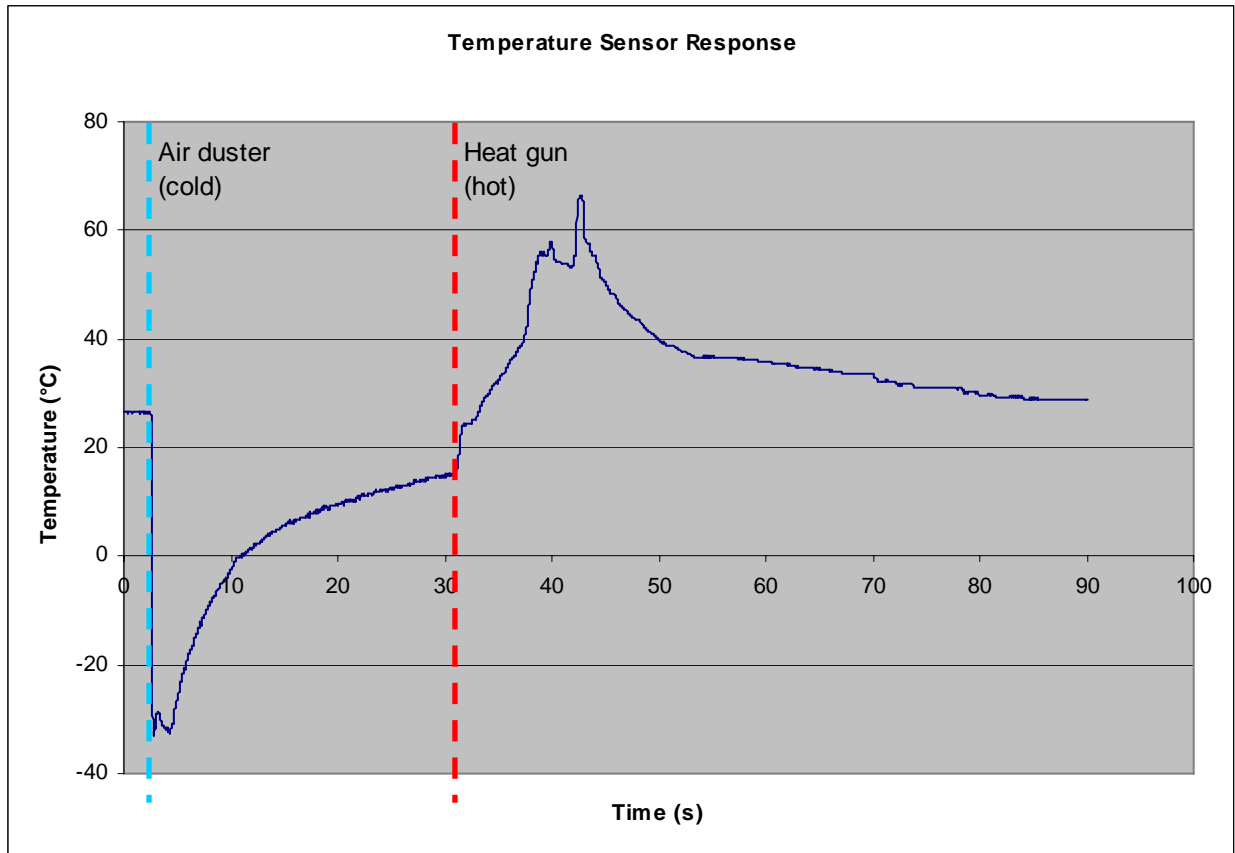


Figure 8. Temperature measurement with the WISP. A can of compressed air (held inverted) was used to generate a low temperature impulse, visible at about 2.5s in the figure. The temperature reported by the WISP is allowed to recover toward room temperature for about 30s, at which time a heat gun is used to generate a high temperature impulse.

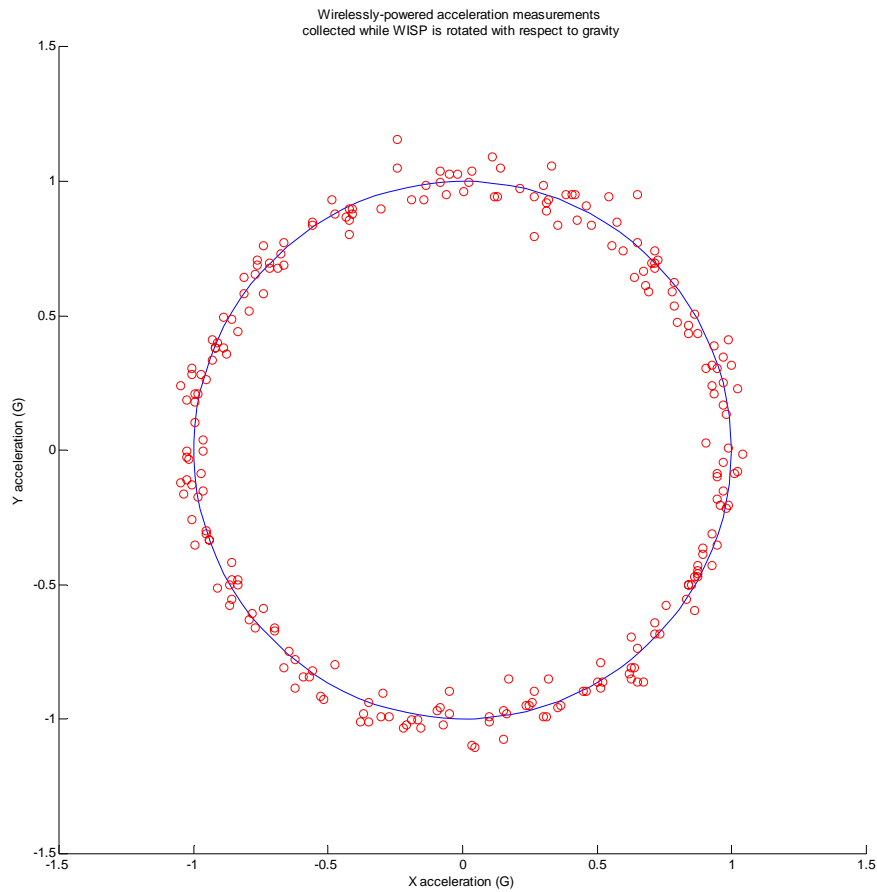


Figure 9. Data from 2 of the axes of a wirelessly powered triaxial accelerometer. [23] The WISP was rotated with respect to gravity to generate this figure. As the x- and y- sensitivity axes of the WISP change orientation with respect to gravity, the proportion of earth's constant 1G of gravitational acceleration reported by the x- and y-axis sensors changes.

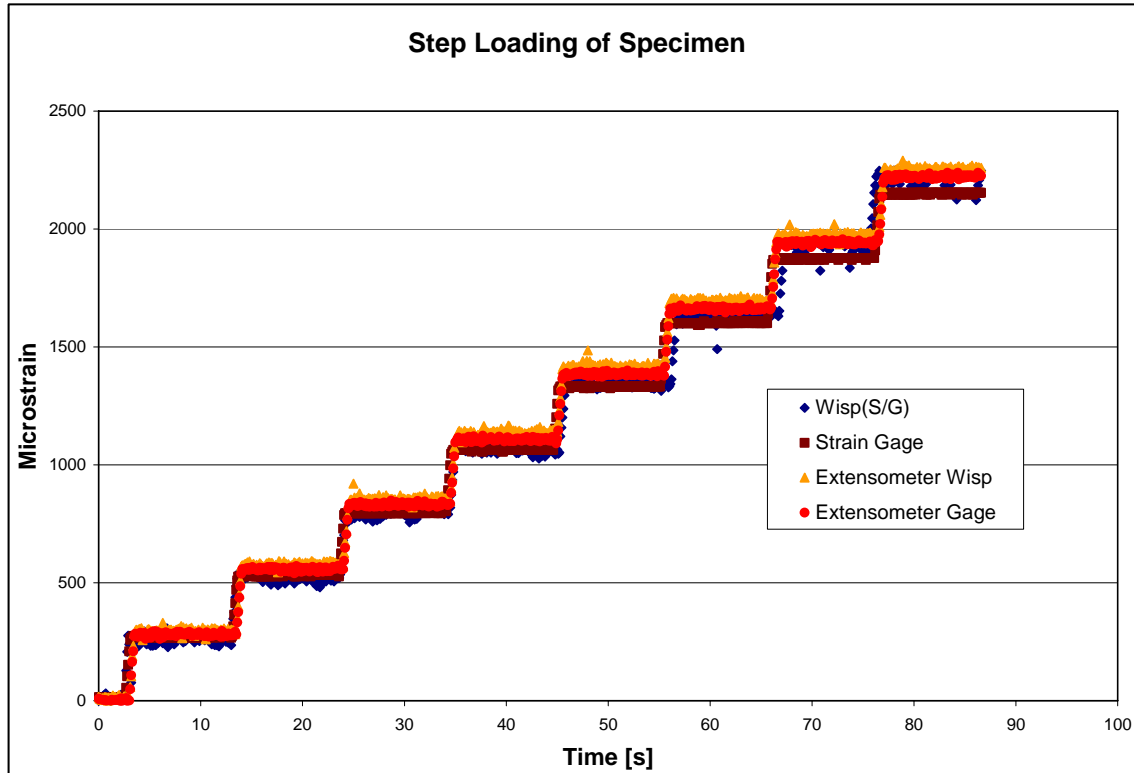


Figure 10. Strain recorded during the step loading of a specimen. [24] The 4 traces shows data collected by the WISP strain gage “Wisp(S/G)”, the same transducer powered and read conventionally (“Strain Gage”), and a more accurate ground truth sensor measured simultaneously with the WISP (“Extensometer Wisp”) and simultaneously with the conventional strain gage (“Extensometer Gage”).

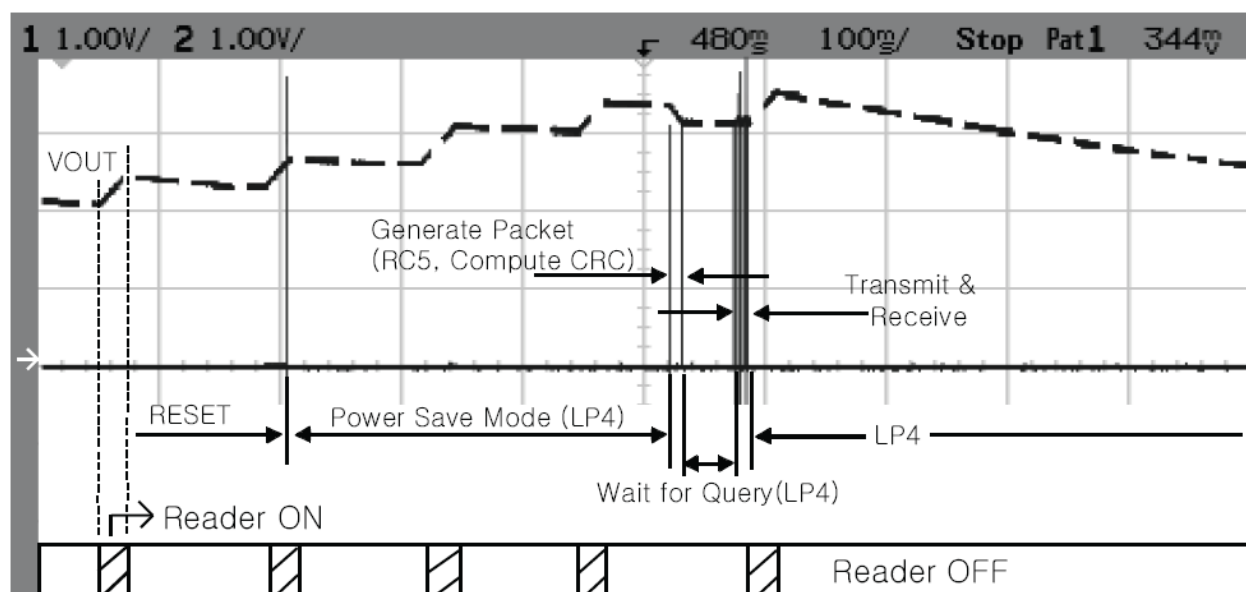


Figure 11. Trace of Vout (power supply) before, during, and after RC5 encryption. While the Reader is ON (i.e., sending queries), the WISP’s voltage level stairs up. The ramp up from 0 V is omitted on the left. The voltage supervisor wakes up the WISP from LP4 when the voltage level exceeds 3.3 V, and WISP begins its computation (“Generate Packet”). When the reader receives the WISP’s response, the reader stops sending queries, cutting off RF-power to the WISP. This is observed as a gradual decline of voltage at the right side of the figure. The WISP first enters LP4 and then resets as the voltage level falls below the minimum operating voltage. The total latency from 0 V until the end of RF response transmission in this case is approximately two seconds.

(From [25] With Permission.)