A Capacitive Touch Interface for Passive RFID Tags

Alanson P. Sample, *Student Member, IEEE*, Daniel J. Yeager, *Student Member, IEEE*, and Joshua R. Smith, *Member, IEEE*

***Abstract*—This paper presents a novel method for incorporating a capacitive touch interface into existing passive RFID tag architectures without additional parts or changes to the manufacturing process. Our approach employs the tag's antenna as a dual function element in which the antenna simultaneously acts as both a low-frequency capacitive fringing electric field sensor and also as an RF antenna. To demonstrate the feasibility of our approach, we have prototyped a passive UHF tag with capacitive sensing capability integrated into the antenna port using the WISP tag. Finally, we describe how this technology can be used for touch interfaces as well as other applications with the addition of a LED for user feedback.**

***Index Terms*—Passive RFID, touch interface, capacitive sensor, transponder**

I. Introduction

Current research efforts in Radio Frequency Identification (RFID) applications are exploiting the low-cost and unobtrusive form factor of RFID tags to serve as the glue between the real (physical) and virtual (electronically-represented) worlds. Traditional examples include the use of RFID tags for automatic electronic tracking of items in supply chains, payment for physical goods with electronically-represented money (vs. printed money), and physical building access with an electronic access card (vs. a physical key).

Recent non-conventional applications are applying the ubiquitous and pervasive nature of RFID to connect the physical and virtual world in new ways. Specifically, RFID is being used as a ubiquitous interface, embedded throughout the environment for data collection or to seamlessly call for services and information. Examples include the implementation of a living environment augmented with RFID to enhance the quality of life and independence of elderly citizens [1]. In this example, participants wear small mobile RFID reader bracelets that report interaction with tagged objects. Activities can be inferred from this data and reported to caregivers. In [2], tags function as symbols in an RFID-augmented environment that represent actions and services available to the user; a cell phone enhanced with a mobile near-field RFID reader "touches" the tag to gain information or to activate a service.

These kinds of applications are based on a very simple binary model: the user's behavior determines whether the tag is inside or outside the interrogation field of the RFID reader. Enabling richer user-tag interactions by giving the user explicit control over how the tag is used and what information it sends has the potential to unlock new applications of RFID. Furthermore, it can potentially mitigate many of the current privacy and security issues relating to RFID used in passports, credit cards, and other RFID applications that involve personal data.

One can envision a simple scenario where the user touches an input on a passive UHF RFID tag, which communicates with a nearby RFID reader, in order to control a light switch. In this case the need for the individual to carry a mobile RFID reader in order to participate in an RFID-enhanced environment is not necessary. Alternatively a shopper purchasing items with a RFID enabled credit card could choose when to transmit his/her private data by touching an input on the card. This would thwart an attacker from wirelessly stealing passport or credit card information while the tag is in a mailing envelope, purse, or wallet; the tag must be touched to be enabled at the intended time of use.

The research presented here supports these types of new applications by allowing the user to interact directly with passive RFID tags via an embedded touch interface that does not change the tag's form factor or cost. Large scale passive tag production requires minimum cost per fully-assembled tag. Thus, a key challenge for incorporating new functionality into passive RFID tags is maintaining a cost-effective manufacturing process. Furthermore, the thin, unobtrusive "label" form factor of RFID tags is important in many applications. Sensing schemes that require no changes to the tag form factor or manufacturing processes therefore have significant practical advantages over less-integrated sensor tag schemes.

This paper presents a technique for adding user touch sensing into a passive RFID tag in a fashion that is fully compatible with existing UHF tag form factors and manufacturing processes: the RFID antenna functions simultaneously as a capacitive touch sensor and UHF RFID antenna. The primary function of the antenna remains to

Manuscript received December 31, 2008; The work presented in this paper was funded by Intel Research Seattle.

A. P. Sample and D. J. Yeager are with University of Washington, Department of Electrical Engineering, Campus Box 352500, Seattle, WA 98195-2500 USA. (e-mail: {alanson, yeagerd}@ee.washington.edu).

J. R. Smith is with Intel Research Seattle, 1100 NE 45th Street, 6th Floor, Seattle, WA 98105 USA (e-mail: joshua.r.smith@intel.com)

provide power and communication for the tag. Additionally, the tag's circuitry uses the antenna's low frequency self capacitance as an electric field touch or proximity sensor. When the user touches the input area on the tag's antenna, the RC time constant of the capacitance sensor is measured and a touch event is reported to the reader. The RFID tag user interface is further developed with the addition of an LED into the WISP platform for event notification or feedback.

In contrast, other methods for combining input devices with tags RFID tags are not compatible with existing processes. For example, there are a variety of prior examples of a push button or mechanical interface for RFID tags. The input devices in [3,4,5] rely on the inclusion of a mechanical switch that couples the RFID chip to the antenna. Closing the mechanical switch enables the RFID chip to communicate with a reader. Present RFID assembly techniques rely on a flip-chip process where the IC's two or three antenna pads are directly bonded to the antenna using a conductive adhesive [6]. The inclusion of a third device, such as a switch, would not be compatible with this low-cost assembly technique, and would yield a much more expensive finished product.

The organization of this paper is as follows: Section II describes the general design and operation principles of RFID tag enhanced with a capacitive touch interface. Section III presents the implementation and performance of a UHF RFID tag with a capacitive touch input and an LED output for user feedback. Finally, applications are discussed in section IV and a conclusion in section V.

II. PASSIVE RFID CAPACITIVE SENSING ARCHITECTURE

There are a variety of capacitive sensing methods that can be utilized to identify a touch event [7]. The simplest method relies on measuring the rate at which the sensing capacitor charges and discharges when different materials are placed within its electric fields. In related work the authors in [8] present an analysis of capacitive sensors made from conductive ink printed on paper, for use in interactive displays and print media. This sensor manufacturing method is directly applicable to RFID antenna construction which typically uses conductive ink printed on a plastic substrate.

In order to achieve a low-cost RFID touch interface, our proposed method relies on using the tag's antenna for power and communication while at the same time using it as a capacitive sensing element. The key is to take advantage of the frequency separation between the RFID reader's carrier signal (HF or UHF bands) and the low frequency RC time constant of a capacitive sensor (DC to LF). By separating these two signals, the antenna will operate as a dual band device: the UHF signal only interacts with the radiating structures and the low frequency electric fields only interact with the capacitive sensing circuitry.

As an example of how an RFID antenna can form a capacitive sensing element, consider a simple dipole antenna. Inherently, at DC, the two halves of a dipole form a capacitor with energy stored in fringing electric fields. This capacitor can be charged by injecting a DC voltage across the two ports of the antenna. Even though the two halves of the antenna are at a different DC potential, the AC characteristics of the antenna are unchanged, and thus the dipole will continue to radiate energy (and through reciprocity receive energy).

Once charged, the voltage on the capacitor (antenna) will exponentially discharge in relationship to the resistance between the two capacitive plates (two sides of the dipole). When the dielectric constant of the material inside the electric fields is changed (e.g. when the user touches the sensor), the RC time constant changes measurably, thus allowing detection of a touch event.

Figure 1 shows a block diagram of an RFID tag enhanced with a capacitive touch circuit. The UHF antenna forms a parasitic capacitor at DC (depicted as dotted lines), which is used as the touch sensing element. The antenna is simply connected to the RFID chip through the two standard RF pads. As with traditional tags, the antenna's impedance (at the RF design frequency) is matched to the complex conjugate of the analog front-end of the RFID chip for maximum power transfer. In order to insure proper operation of the analog front end, a low-pass filter presents a high impendence path blocking the RF signal from the capacitive measurement circuits. Utilizing a first-order RC low pass filter, resistance in the order of 200 kΩ and capacitance in the order of 5 pF meets the design criteria sufficiently.

The operation of an RFID tag enhanced with the touch sensors is as follows: Once the RFID tag is powered on and operating, the I/O port of the capacitive sensing circuit charges the positive side of the antenna. This DC signal is blocked from interfering with the Analog Front End of the IC due to the rectifier's AC coupling capacitors.

After the positive side of the antenna capacitor is charged to the regulated voltage of the IC, the direction of the port is changed from an output to an input and a digital timer is started to measure the rate of discharge. In order to register a user touch, the time at which the voltage on the capacitor reaches the threshold of the input port is compared to a calibrated or hard-coded threshold time value. Having the ability to change the trigger threshold for a touch event allows a single tag IC to be used in multiple antenna inlays with different absolute DC capacitances.

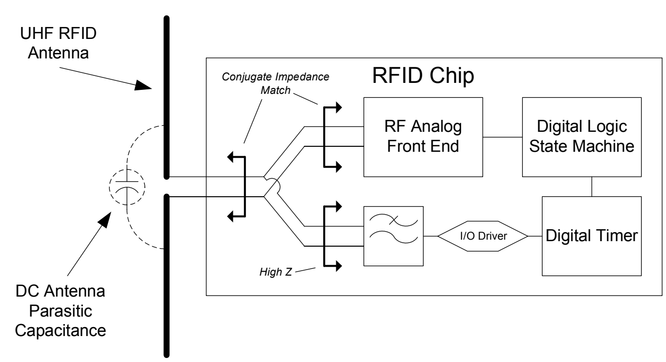

Figure 1 Block diagram of the capacitive touch sensor enhanced RFID tag. The antenna forms a sensing capacitor at low frequencies and its RC discharge rate is measured with the digital timer.

Though the frequency separation of the RFID communication and sensing signals allows for isolation from each other, the event of the user touching the tag does have an effect on the antenna's resonant frequency. The phenomena of tags being detuned by environmental objects is well documented in [9,10]. Thus, careful antenna design is necessary to minimize the potential for the user to detune antenna. The simple dipole antenna discussed above is only one example of the wide variety of planar antenna structures that are suitable for RFID tags. Alternative antenna designs have the potential to increase the robustness against dutuning; however, for the purpose of demonstrating the feasibility of this sensing method, only the performance of a dipole antenna enhanced is discussed.

The authors believe that the proposed capacitive sensing method has the potential to enable a low-cost, mass manufactured solution for user input in passive RFID. In particular, the antenna can still be printed with conductive ink onto a variety of substrates. The complexity of assembly remains the same since only the two original RF ports are needed by the touch sensor.

Incorporating the capacitive measurement circuit into the tag's IC would not significantly add to the overall die size. The digital timer and single digital I/O port would take up a relatively small amount of current consumption compared to the space allocated to the RF charge pump and EEPROM on a normal tag. Finally, due to the wide frequency gap between the RF input signal and the operating frequency of the capacitive sensing circuit the low-pass filter can be manufactured with less accurate, but space efficient, on-chip passive components.

III. Implementation and Experimental results

An EPC Class 1 Generation 2 tag has been prototyped to demonstrate the feasibility of capacitive sensing through the tag antenna. Sensor measurements can be reported to a commercial RFID reader in a variety of forms: sensor measurements can be encoded in the tag's ID, used to prevent/allow ID transmission or retrieved through a read operation to user memory. Finally, the application layer decodes and displays tag sensor information reported by the reader.

The tag prototype is shown in Figure 2. The antenna consists of copper foil on an FR4 substrate. The antenna is laminated with an insulator to prevent resistive loading of the capacitive sensor. Three fins between the dipole branches increase the sensitivity of the capacitive sensor. Finally, a programmable passive tag is connected to the antenna for capacitive sensing and EPC Class 1 Generation 2 communication.

The tag prototype leverages the WISP (Wireless Identification and Sensing Platform) to perform the capacitive sensing and RFID communication. The WISP is a programmable battery-free sensing and computational platform designed to explore sensor-enhanced RFID applications. The WISP uses a 16-bit, ultra-low-power microcontroller to

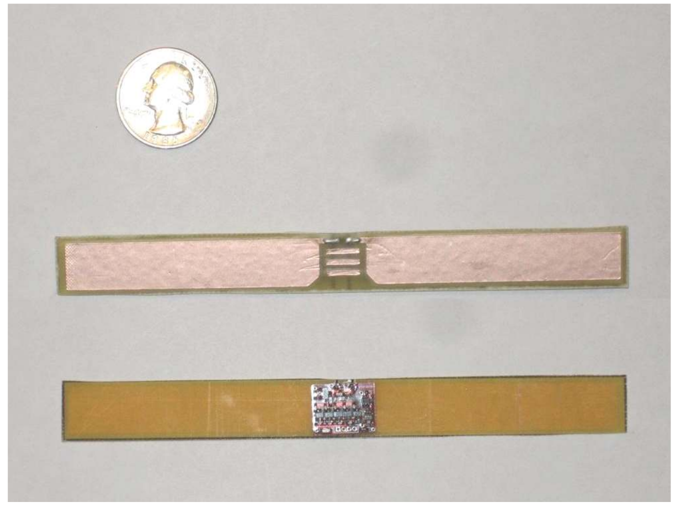

Figure 2 Image of the passive UHF RFID tag with a capacitive touch input and LED output for feed back.

emulate the EPC Gen2 protocol and perform sensing and computation tasks while operating exclusively from harvested RF energy. A full discussion of the WISP's design and performance is presented in [11].

The features shown in Figure 1 were added to the WISP in this prototype including a low pass filter and sensing routine to measure the discharge time constant of the antenna. Commercial ASIC tag implementations including this touch interface would also require addition of these components including the low pass filter, bidirectional I/O driver and digital counter for measuring the antenna RC time constant.

Adtionally there are a number of applications in which user feedback is necessary; to explore theses scenarios an LED is located on the lower left corner of the WISP. Although to date, the incorporation of a LED in to RFID ICs is not readily available, recent work in semiconductor optics has shown promising results. The authors in [12,13] have developed CMOS compatible LEDs operating at 2-3 volts. It is important to note that even with a CMOS compatible process, significant packaging and charge storage issues would have to be overcome. Alternatively, a two chip system (RFID IC and LED) assembled by 3D wafer stacking could be used.

The usage model for the touch-enhanced RFID tag demonstrated here is straightforward. When in the presence of an RFID reader, the touch tag transmits a standard EPC ID. When the users place his/her finger on the input region of the tag (center of the antenna) the LED flashes giving positive feedback that the touch event was registered by the tag and an alternate EPC ID encoding the touch event is transmitted to the reader. Finally, the reader passes the stream of IDs to a host computer which displays the touch event by changing the color of an image of a light bulb based if the sensor is touched. From the user's point of view the transaction is seamless; by touching the tag's sensor, the image on the screen is activated and deactivated.

Other encoding scenarios can easily be implemented. The touched and un-touched states can have different responses: no ID, a dummy ID, or an intended ID may be transmitted, depending on the application. For example, in credit card and passport scenarios it may be desirable that no ID is transmitted unless the sensor is touched.

A. Antenna Design

The design challenge is to create a 902-928 MHz antenna not adversely affected by the presence of the user's finger while simultaneously being sensitive enough for the RC time constant to be measured. This was accomplished by using Ansoft HFSS for simulation and an automatic stencil cutter for rapid prototyping of the antenna. The antenna was designed for 50 ohms impedance for ease of testing. Additionally, the WISP's analog front end has landings for a discrete matching network which was also tuned for a 50 Ω impedance.

When considering how to incorporate the touch sensor it is useful to recall the operating principal of a half-wave dipole antenna. Each arm of the antenna is a quarter wavelength long and open at the ends. When driven at resonance, a sinusoidal standing wave pattern occurs with an oscillating voltage maximum at the ends of the antenna, and a voltage null at the feed point. Thus the resulting electric field in the vicinity of the antenna port is small in magnitude and the effect of the user's finger is negligible, making an ideal location for the touch sensor.

It is well documented the nearby objects can have a large effect on UHF RFID tag performance as reported in [9,10]. However in these publications the authors consider the effects of metal planes and objects larger than the scale of the antenna. In the case of the touch sensor, the space that the tip of the finger comes in contact with is sufficiently small in size compared to the overall antenna; thus if the user approaches the tag perpendicular to the antenna axis, the interference from the hand is tolerable.

The dipole antenna shown in Figure 2 was widened to increase the DC capacitance for the sensing circuit, as well as increase the bandwidth at resonance to help avoid detuning. A design frequency of 920 MHz was used to allow for detuning to a lower frequency. When the user activates the touch sensor in the middle antennae, the change in DC capacitance is approximately 5-6 pF. Figure 3 shows simulated and experimental S11 results for the touch sensor augmented dipole antenna. The simulation shows a decrease in the magnitude and a frequency shift to left. This is expected because the increased capacitance of the finger decreased the resonant frequency which affects the ability of the antenna to resonate. The experimental data confirms the trend expressed by the simulation. However, due to variation in the manufacturing of the antenna and the lack of an anechoic chamber for precise measurement, the "un-touched" resonant peak is shallower than the simulation.

B. Capacitive Touch Sensor performance

In order to add capacitive sensing capability to the WISP, a simple RC low pass filter was added to one of the data I/O pins on the MSP430. As discussed, this creates a high impedance path that blocks the RF signal from reaching the capacitive sensing circuitry in the tag. To create a consistent RC discharge time, an explicit parallel resistor in the megaohm range was added to provide a discharge path for the touch sensor.

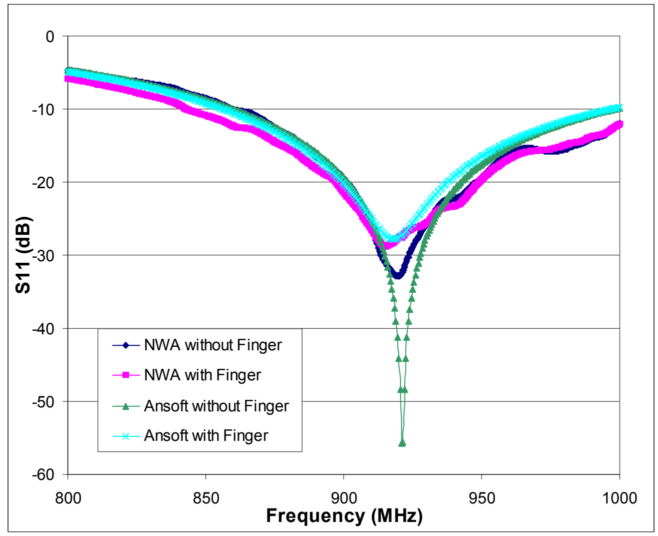

Figure 3 Simulated and experimental results showing the S11 response of the RFID touch antenna when active by the user's finger and when left on touched.

In order to take a touch measurement, the WISP charges the antenna by outputting a logical one on a digital I/O pin. The result is that a DC bias of 1.8 V (operating voltage) is applied to the positive port of the antenna. The AC coupling capacitors of the harvester prevent the DC signal from discharging through the RF rectifier. Next the microcontroller sets the I/O pin to an input and starts the digital timer. When the voltage level on the capacitor drops below the threshold of the input pin, an interrupt stops the timer and records the timer value. If the timed value is above the preset threshold a touch is recorded. The measurement is averaged eight times to improve noise immunity and sensitivity.

Using the existing RFID capabilities of the WISP, the onboard microcontroller embeds the touch sensor data into an EPC-complaint ID and reports the ID via EPC Class 1 Generation 2 RFID protocol. Figure 4 shows an EPC inventory round followed by the measurements events; the top set of oscilloscope traces shows the untouched tag and bottom set shows the user touching the tag. As expected, the presence of the user's finger adds capacitance which increases the RC time constant of the touch sensor.

Figure 5 shows the time series response of three touch events. In this example, the touch tag is configured to transmit raw sensor data back to the reader and host application. The *Timer Count* represents the average of eight consecutive RC discharge times from Vdd to ½ Vdd. This data is then encoded into the EPC ID and transmitted to the RFID reader for data collection. The read rate is 100 queries per second and there are three individual touch events lasting approximately one second each. Additionally, the touch tag is programmed with threshold of 80 counts (determined empirically) which is used to trigger an LED blink event on the tag.

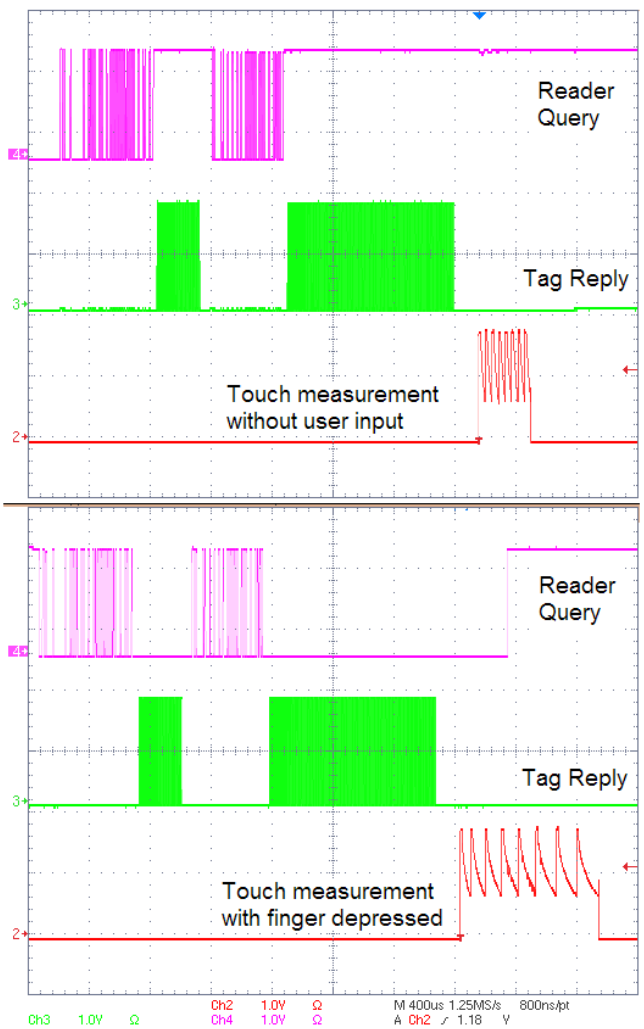

Figure 4 Two RFID tag touch measurement events showing EPC Gen2 protocol and senses capacitor RC discharge. The top plot shows the untouched event and the bottoms plot shows the increase in discharge rate caused by the added capacitance of the user's finger.

IV. Applications

The technique presented here may be used for capacitive user input or other capacitive sensing applications. The user input applications can be divided into RFID-specific input and general-purpose input categories. RFID-specific input means that the primary purpose of the device is RFID (that is, identification, for access control or other purposes), but the behavior of the RFID tag is controlled by the user input. General-purpose input means that the RFID system is being used as a channel for power and data, but the user input is the ultimate purpose.

The RFID-specific input applications can help address many of the known privacy and security problems of RFID by giving the user control over when and what type of data is transmitted by the tag. A basic attack involves an unauthorized RFID reader simply interrogating a target tag to track the user or clone the tag's ID. U.S. passports with embedded RFID tags were given a mylar pouch to shield RF signals from activating the tag. Unfortunately this solution relies on the user to be

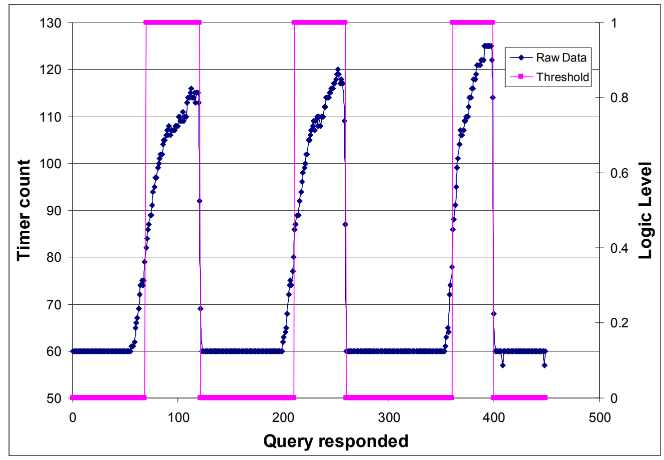

Figure 5 Raw capacitive sensor data and identified touch events transmitted to the RFID reader form the RFID tag.

aware of the privacy and security risk associated with RFID, and it requires them to be vigilant about protecting their personal information.

The capacitive input technique presented here could enable a more elegant and cost effective solution to RFID access control. Figure 6 shows a touch-enhanced RFID tag that has been built into the form factor of a credit card. The tag indicates, via an LED, that a reader is making a read query. The user then has the option to explicitly authorize the tag to respond. RFID-based payment mechanisms can greatly benefit from bearer control by preventing unauthorized readers from conducting transactions (especially payments) without explicit authorization from the card owner. The authors in [14] have demonstrated a similarly system where direct user inputs to a RFID tag enables and disables communication. In this case a 3D accelerometer is used as an orientation sensor and the user performs a secreted handshake or gesture which is analyzed by the tag for authentication.

If multiple buttons were implemented, numeric keypads for a personal identification number (PIN) input could be added to credit cards. This could provide even higher levels of security than single button authorization: if the card were lost, the thief could not authorize an RFID read, thus preventing unauthorized use of RFID access keycards, passports and credit cards.

It may be possible to implement a numeric keypad using a single capacitive sensor channel. First, one would implement a linear position sensor by changing the width of the electrode along the position sensitive dimension, so that touch location was encoded by capacitance value. Then one would wrap this linear position sensor in serpentine fashion through the keypad locations. With 12 distinguishable capacitance values, a conventional numeric keypad could be implemented.

The general-purpose applications of the technology are also exciting. Fully wireless, battery-free controllers such as light switches could be implemented as thin, unobtrusive, and inexpensive RFID tags adhered to walls, furniture, or elsewhere. If a linear controller is deployed, it could function as a wireless light dimmer controller, fan speed controller, or

Figure 5 Touch enhanced UHF near-field RFID tag in the form factor if a credit card.

other analog control device. Input devices such as remote controls could also be implemented using this technology. The minimal form factor and potential low cost would be a good match for plush or plastic toys. The technique could also be used for user presence detection. For example, it could be integrated into furniture to detect user presence and pose.

Pure sensing applications (non-user interface) are also compelling. The label form factor and low cost architecture enable integration of a capacitive sensor tag into many types of end-user packaging. For example [15] uses an external capacitive sensor to measure the level of milk in a carton. Alternatively the capacitive sensor could measure a wider variety of phenomenon by placing a material whose dielectric constant is affected by other physical parameters in the vicinity of the sense electrodes. There are a number of sensors that work in this fashion including humidity, temperature, pressure and displacement.

V. FUTURE WORK

The touch interface presented in this article is a proof of concept for the dual use of an RFID antenna for traditional power and communication, as well as for capacitive sensing. Further work will be necessary to design a robust antenna that is optimized for both robust, wideband RF performance and high sensitivity for capacitive sensing. The tag's integrated circuit will need to be modified to include the RF isolating low pass filter, a bidirectional I/O circuit, and the digital timer for measuring the RC discharge.

Many tag designs include an inductive short for tag impedance matching. If the tag application is less cost-sensitive, additional capacitive sensing terminals may be added to the tag, which allows for traditional tag antenna designs. One result of using an antenna that is isolated at DC (i.e. no inductive impedance matching strap) is that improvements in Elector Static Discharge (ESD) protection will need to be made. Presently, the Impinj Monza chip has input protection rated to 1,000 V and has been shown to withstand shocks of over 4000 V [16].

VI. CONCLUSION

This paper presented a method of measuring capacitance in an RFID sensor tag that requires no changes to form factor or manufacturing processes from ordinary, non-sensor passive RFID tags. This technique has the potential to solve a number of known RFID privacy and security problems, by giving the user of the tag explicit control over whether it responds to a reader. Beyond security and privacy, it enables other tag user interfaces, where the goal is user interaction with the environment. For example, touch sensor tags could enable simple input devices (embedded in objects such as toys, adhered to walls, etc) that are unobtrusive, wirelessly powered, and potentially inexpensive. Finally, this technology could enable other types of capacitance-based environmental sensing without requiring any change in the form factor or manufacturing processes from today's passive RFID tags.

REFERENCES

[1] Matthai Philipose, Kenneth P. Fishkin, Mike Perkowitz, Donald J. Patterson, Dieter Fox, Henry Kautz, Dirk Hahnel, "Inferring Activities from Interactions with Objects," *IEEE Pervasive Computing* ,vol. 03, no. 4, October-December, 2004, pp. 50-57.

[2] Riekki, J.; Salminen, T.; Alakarppa, I., "Requesting Pervasive Services by Touching RFID Tags," *Pervasive Computing, IEEE* , vol.5, no.1, pp. 40-46, Jan.-March 2006

[3] Lindsay, Jeffrey Dean (Appleton, WI, US), Velazquez, Heriberto Flores (Neenah, WI, US), Chen, Fung-jou (Appleton, WI, US), Wagner, Eric Francis (Sherwood, WI, US). "Activating a data tag by load or orientation or user control." USA Patent 7151455. December 2006

[4] 31 Dec 2007. "Press Release." smartcodecorp. 19 May 2006. SMARTCODE Corporation. <www.smartcodecorp.com>.

[5] M. Philipose, J. R. Smith, B. Jiang, K. Sundara-Rajan, A. Mamishev, S. Roy, "Battery-Free Wireless Identification and Sensing" *IEEE Pervasive Computing*, vol. 4, no. 1, Jan 2005, pp. 37-45.

[6] Finkenzeller, Klaus. RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification. Second Edition. New York, NY, USA: John Wiley & Sons, Inc., 2003.

[7] L. K. Baxter, Capacitive sensors: design and applications, IEEE press, 1997.Kocer, F. and M. P. Flynn. "A new transponder architecture with on-chip ADC for long-range telemetry applications," *IEEE Journal of Solid-State Circuits*, vol. 41, no. 5, May 2006, pp. 1142-1148.

[8] Unander, Tomas; Nilsson, Hans-Erik; Oelmann, Bengt, "Printed touch sensor for interactive packaging and display," *Polymers and Adhesives in Microelectronics and Photonics, 2007. Polytronic 2007. 6th International Conference on* , vol., no., pp.12-17, Jan. 16 2007-Yearly 18 2007

[9] Xianming Qing; Zhi Ning Chen, "Proximity Effects of Metallic Environments on High Frequency RFID Reader Antenna: Study and Applications," *Antennas and Propagation, IEEE Transactions on* , vol.55, no.11, pp.3105-3111, Nov. 2007

[10] Dobkin, D.M.; Weigand, S.M., "Environmental effects on RFID tag antennas," *Microwave Symposium Digest, 2005 IEEE MTT-S International* , vol., no., pp. 4 pp.-, 12-17 June 2005

[11] Sample, A.P.; Yeager, D.J.; Powledge, P.S.; Mamishev, A.V.; Smith, J.R., "Design of an RFID-Based Battery-Free Programmable Sensing Platform," *Instrumentation and Measurement, IEEE Transactions on* , vol.57, no.11, pp.2608-2615, Nov. 2008

[12] Chilukuri, Kamesh, "Monolithic CMOS-compatible AlGaInP visible LED arrays on silicon on lattice-engineered substrates (SOLES)." Semiconductor Science and Technology 22(February 2007): 29.

[13] Brown, 31 Dec 2007. "ST lights up silicon LED for CMOS fab lines." www.eetimes.com. 29 November 2002. EE Times. <http://www.eetimes.com/story/OEG20021029S0027>.

[14] Czeskis, A.; Koscher, K.; Smith, J. R.; and Kohno, T., "RFIDs and secret handshakes: defending against ghost-and-leech attacks and unauthorized reads with context-aware communications".

In Proceedings of the 15th ACM Conference on Computer and Communications Security, Alexandria, Virginia, USA, October 27 - 31, 2008.

[15] Yeager, D.J.; Powledge, P.S.; Prasad, R.; Wetherall, D.; Smith, J.R., "Wirelessly-Charged UHF Tags for Sensor Data Collection," *RFID, 2008 IEEE International Conference on* , vol., no., pp.320-327, 16-17 April 2008

[16] Impinj Whitepaper, "ESD and the RFID Tag," http://www.impinj.com/workarea/showcontent.aspx?id=2539, September 2005