Towards Autonomously-Powered CRFIDs

Shane S. Clark, Jeremy Gummeson, Kevin Fu, Deepak Ganesan
University of Massachusetts Amherst, Dept. of Computer Science
{ssclark,gummeson,kevinfu,ganesan}@cs.umass.edu

ABSTRACT

Batteryless Computational RFID (CRFID) devices present exciting possibilities for ubiquitous computing applications. They require minimal maintenance, are cheap to manufacture, and have small form factors. However, CRFIDs lack autonomy because of the need for constant power from an RFID reader—hindering deployment. In this paper, we propose hybrid power harvesting techniques as a mechanism for designing autonomous CRFIDs. We show that a CRFID equipped with a 11.4 cm^2 solar panel can enable autonomous computation, storage, and sensing as well as a two-fold increase in communication range with a reader and a three-fold increase in sensing rate. Energy management challenges specific to CRFIDs include high variability of energy harvesting, workload sensitivities to capacitor size, the difficulty of measuring voltage levels while conserving energy, and risk taking to insure against interrupted computation. We propose simple heuristics to select appropriate capacitor sizes and circuitry to monitor voltage levels on autonomous CRFIDs.

1. INTRODUCTION

An emerging model of RFID goes significantly beyond mere identification. Future RFID applications will require tags that also perform minimal sensing, computation, and storage. In contrast to RFIDs that only perform identification, Computational RFIDs (CRFIDS) [6] such as Intel's WISP [8] provide von Neumann architectures that are completely reprogrammable and yet rely on a small capacitor rather than a battery.

Recent work has pointed out several potential benefits offered by CRFIDs over battery-powered platforms such as Motes [1, 6]. Mote-class platforms are fundamentally limited by the use of batteries, which are toxic, and inevitably incur high cost for servicing (either for replacing batteries or removing batteries to avoid toxic waste). Batteries also have a limited number of charge cycles, making them unsuitable for use in harvesting-based environments that experience frequent charge and discharge cycles. Batteryless CRFIDs, however, are completely powered via harvested energy stored on a capacitor. The longevity and effectiveness of a capacitor is tied to the operating environment (e.g., heat, corrosion, abuse with excessive voltage) rather than the number of charge cycles. Because capacitors can sustain virtually unlimited charge cycles and are more environmentally friendly, a CRFID isolated from the elements has no components requiring regular service or replacement.

The longevity of CRFIDs, combined with their small form factor, allows them to be used for sensing and computation in places where a battery-powered device cannot be placed. For example, CRFIDs can easily meet the size and weight constraints required to tag small animals for the purpose of tracking them [9] without the risk of battery leakage. The perpetual nature of CRFIDs also enables them to be used in applications such as building or bridge monitoring, where nodes need to be embedded in concrete structures for decades.

1.1 Limitations of CRFIDs

Unfortunately, CRFIDs are not a ubiquitous computing and sensing panacea. Designing CRFIDs that can perform more complex tasks involving sensing, computation, and storage brings several new challenges. A key limitation of CRFIDs is the reliance on a dense deployment of RFID readers. CRFIDs must be placed such that each device harvests enough energy to compute and sense. When energy from readers is intermittent, for example when mobile readers are used, a CRFID can only remain outside of effective harvesting range for a short period of time before it loses power completely. This lack of autonomy necessitates carefully planned deploy-

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ments of RFID readers relative to tags and makes such networks expensive to deploy and maintain.

A CRFID's lack of autonomy is exacerbated by the observation that its communication performance degrades rapidly as distance from a reader increases. For example, our experiments show that a WISP that is within a few feet of an RFID reader receives sufficient energy to sample and transmit hundreds of times per *second*, whereas one that is near its maximum reliable distance (4.7 m) may be able to sample and transmit a few times per *minute*. Surprisingly, the primary bottleneck is not the power required for backscatter communication but rather the power consumed for computation and sensing. This rapid performance degradation limits the efficacy of CRFIDs for applications requiring complex processing or frequent sensing.

1.2 Contributions

The central idea in our work is the use of hybrid energy harvesting techniques to extricate CRFIDs from their dependence on readers and thereby achieve autonomous, continuous CRFID computation, sensing, and storage. Such a hybrid-powered CRFID is equipped with a small solar, thermal or vibration harvester to provide a local energy source in addition to energy from the RFID reader.

We show that the use of diverse, complementary harvesting sources has two major benefits. First, it allows sensing, computation, and storage to proceed even while a reader is not in the vicinity. This enables a more flexible approach to placement of readers for applications that do not require real-time data—for example, readers could be mobile and intermittently gather data from CRFIDs. Second, locally harvested energy provides a power boost to the CRFID during active communication with a reader. This increases the range and bit-rate of communication, thereby enabling a sparser and consequently lower cost reader deployment.

Despite the potential benefits of hybrid energy harvesting, harvesting from ambient energy is challenging because of the dynamics of the energy source. The use of small capacitors for energy storage makes this problem acute since a CRFID may quickly lose power and consequently its state. We discuss these challenges and provide hints for CRFID energy management to maximize efficiency and minimize loss of state and outages.

2. HYBRID HARVESTING FOR CRFIDS

The two energy sources that we propose for autonomous CRFIDs are a traditional RF harvesting unit employed by current CRFIDs and a secondary harvesting unit that gathers energy from an ambient source. Our focus is on developing design principles and both hardware and software techniques to utilize the new capabilities achievable by this device.

Conditions	Light intensity	Indoor Solar Power
Full Shading	28 lux	6.6 μW
Partial shading	85 lux	35.9 μW
Diffuse	340 lux	62.5 μW
Direct	1,300 lux	192.0 μW

Table 1: The amount of actual harvested power depends greatly on light intensity. A fully shaded 11.4 cm^2 solar panel produces 29.1x less power than the same panel under bright light conditions

2.1 Harvesting sources

A variety of ambient energy sources may be harnessed to power CRFIDs in the absence of a reader such as solar, thermal, vibrational or ambient RF energies. The harvestable energy rates from such ambient sources vary from less than a μW to a few mW depending on the technology and environment [5].

Introducing ambient energy harvesting to CRFID class devices imports a unique set of challenges, driven by their small form factor and the vagaries of the ambient energy source. A key benefit of a CRFID is its small form factor, which enables truly ubiquitous deployments. (For example, the Intel WISP has a form factor of 3 cm^2.) Therefore, it follows that the size of an ambient harvester should not reduce the deployability of a CRFID system, but enhance its operation. This size constraint greatly limits the amount of harvested energy from a micro-generator.

Ambient energy harvesting also exhibits spatial and temporal variability. For example, the orientation of a solar panel relative to the light source greatly impacts harvested energy. In addition, a solar harvester will observe considerably different levels of light intensity over time, attributable to the presence of occlusions or fluctuations in the light source itself, including complete unavailability over some intervals (e.g., at night or when indoor lighting units are switched off).

The characteristics of ambient energy sources raises an important question: *Can a CRFID perform useful work despite the variability of the energy source and the miniscule amounts of energy harvested from it?*

2.2 Benefits of hybrid energy harvesting

The aforementioned limitations of micro-harvesting units make it difficult to imagine how such small amounts of energy could possibly support an embedded computing device. These small amounts of harvested energy can be effectively used primarily because of technology trends in ultra-low-power microcontrollers and sensors. The power efficiencies of these components are now on

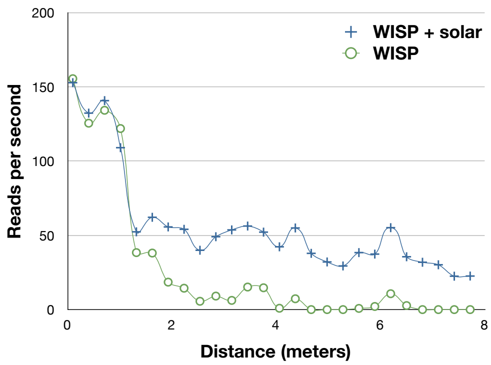

Figure 1: The number of successful tagID reads/sec indoors at a variety of distances with and without a 11.4 cm^2 solar panel. Note that the solar WISP's energy harvesting gives it a consistent advantage at most ranges whereas the non-solar WISP encounters read rates at nearly zero beyond two meters.

the same order of magnitude as the power of a CRFID sized micro-harvester.

Solar WISP: To validate our claim that a small amount of harvested energy can go a long way towards enabling autonomous CRFIDs, we perform a measurement study using a solar-powered CRFID platform. This platform comprises a WISP Revision 4.1 prototype (10 uF capacitor, default clock speed of 1.1 MHz) equipped with an 11.4 cm^2 solar panel. The solar panel is attached to the same storage capacitor used for RF harvesting, allowing power from both sources to be combined into one energy reserve.

Autonomous Operation: Does the Solar WISP generate enough energy for autonomous operation? To answer this question, we measure the harvesting rate of the Solar WISP (Table 1) and the power/energy consumption for different computation, sensing, or storage operations (Table 2). A comparison of these tables shows that power harvested by the solar WISP under different indoor lighting conditions ranges between a few μW to a few hundreds of μW, while the WISP consumes less than 5 μW of power to keep a clock running (Timekeeping mode). Thus, the lowest power states of the Solar WISP can be sustained even in near darkness.

Next, we consider the active mode operation of CRFIDs. While continuous active mode operation would consume more power than can be sustained by the small solar panel, duty cycling the Solar WISP can easily achieve an aggregate power consumption within the bounds of harvestable energy. According to Tables 1 and 2, a duty-cycling approach that transitions between active

System Component	Power/Energy Consumption
WISP Active	412 μW
WISP Time Keeping	4.14 μW
WISP RAM Retention	3.24 μW
Flash Write (8 bytes)	5.4 μJ
10-bit ADC Reading	0.244 μJ

Table 2: The WISP 4.1 has extremely efficient low power states thanks to its MSP430F2132 microcontroller. The disparity between active and low power modes enables flexibility in energy management.

and memory retention power states can achieve between 1.6% duty cycle in full shade and 47% duty cycle under direct light. Being able to periodically enter an active power state means that a CRFID can make forward progress on computation or obtain sensor readings while completely independent of reader infrastructure. While our measurements are of the current generation WISP hardware, technology trends in low-power microcontrollers indicate that CRFID power consumption will decrease further, making micro harvesting more effective.

Increased Read Range and Sensing Rate: In addition to allowing autonomous operation, the small amount of energy harvested by a solar panel improves the read range of our modified WISP while communicating with a reader and improves the sensing rate at long range. The energy from the solar panel can provide sufficient energy to power the MCU, thereby allowing the WISP to communicate at the maximum range of its backscatter circuitry rather than the maximum effective RF harvesting range. Alternately, the extra energy can be used for additional computation such as sensor data filtering, signal processing, or trend analysis.

To quantify the read range and sensing benefits, we performed two experiments using the WISP with and without a solar panel. Using Intel's firmware, the solar WISP achieved more than twice the maximum read range of the unmodified WISP (see Figure 1). Additionally, the solar panel tripled the sensing rate at longer distances. To demonstrate this, we wrote a test application that takes and reports a sensor reading upon receiving a voltage supervisor interrupt. Using an unmodified WISP at 3 m from a reader, we measured a sensing rate of 77.8 reads per second. The same experiment achieved 235 reads per second using the solar WISP under bright office lighting conditions(1,300 lux).

Thus, our results show that *a little harvested energy can go a long way* towards enabling autonomous CRFID deployments and long read ranges from readers to tags.

3. HINTS FOR μENERGY MANAGEMENT

As we have shown, a small amount of ambient energy harvesting can provide flexibility for more effective computation, sensing, storage, and communication on CRFIDs. However, the added flexibility requires careful energy management at relatively small timescales because of sensitivities to minute perturbations in energy. Below we provide several design hints on how future CRFIDs could exploit the flexibility of hybrid power harvesting with micro energy management.

Choose Minimal Capacitors: Capacitor size is a surprisingly important choice for CRFIDs, as it allows the platform to balance responsiveness to energy dynamics and tolerance to energy outages. A large capacitor size enables a CRFID to tolerate energy outages, maintaining a continuous notion of time and avoiding loss of state. This can be useful for applications requiring timestamping of sensor data or for long-running cryptographic computation tasks. However, a large capacitor has a longer charge cycle than a small capacitor, and takes more time to charge up to a nominal operational voltage (batteries have a sharper charge curve making nominal voltage less of an issue). As a consequence, a CRFID with a large capacitor would be less responsive and unable to take advantage of short bursts of ambient energy availability. The issue of responsiveness is particularly important for applications that require frequent sampling or high duty-cycle operation.

An ideal capacitor size enables a CRFID to survive the longest expected harvesting outage and no longer. For example, assume that a WISP needs to maintain timekeeping (see Table 1) for a maximum outage duration of 8 hours (typical night-time duration). If the initial capacitor voltage were 4 V (a high but safe operating point for all components), and the final voltage 1.8 V (the minimum supported by the MCU), we can compute that the appropriate capacitor size is ~ 25 *m*F.

Measure Energy Efficiently: A CRFID must be aware of its available energy in order to maximize efficiency, but monitoring the energy level of the capacitor does not come for free. Using an analog-digital converter (ADC) to poll the voltage level, for example, consumes more than 1% of the total energy available in the WISP's capacitor for each sample (see Table 2), and should be avoided whenever possible. An alternative approach is the use of interrupt-driven notifications. A voltage supervisor can wake a CRFID when the capacitor charge crosses a specific voltage threshold set in hardware. Although attractive from a software convenience standpoint, an analog supervisor circuit consumes a small amount of constant quiescent current, whereas an ADC can be turned off when not polling.

The differing characteristics of these methodologies do not lend themselves to an obvious one-size-fits-all solution. A computationally heavy workload or frequent sensing operations will result in many capacitor charge and discharge cycles. An ADC must poll the capacitor at least once per cycle, resulting in higher power consumption. Conversely, a computationally light workload requires a small number of energy measurements, causing the constant power draw of the voltage supervisor to become expensive as compared to a small number of ADC reads. To illustrate this tradeoff, we note that a single reading of the 10-bit ADC on the WISP 4.1 is equivalent to running its voltage supervisor for 0.35 seconds (based on rated consumption from the supervisor data sheet). Therefore, a sensor application requiring a capacitor voltage measurement per sensor read will be better off using the ADC for sensing rates less than 2.9 Hz.

Support multiple voltage thresholds: The different subsystems of a CRFID have different requirements for nominal operational voltage. For example, the MSP430 operates at 1.8 V, but requires 2.0 V for an ADC read and 2.2 V for a write to flash memory. These differing voltage requirements can present challenges because the ability to perform an operation depends on energy availability and voltage levels determined at run time.

Differing voltage thresholds can be exploited, however, to maximize power efficiency by always using the minimal voltage required for a given operation. A variable output voltage regulator can accomplish this by adjusting as necessary for each task. Less constrained, battery based devices typically use a fixed voltage level such that all operations are available at all times as a matter of convenience, but this policy is wasteful of the little energy that a CRFID can store.

Take risks with state management: When power loss is unavoidable, a CRFID must take steps to minimize or completely avoid loss of state by storing it to nonvolatile memory. However, care must be taken to minimize the energy consumption of such storage. Without ambient power harvesting, conservative checkpointing strategies are necessary to preserve state. For instance, if an RFID reader goes out of range, the contents of RAM could quickly vanish. Mementos implemented conservative checkpointing strategies because of an assumption that complete power loss is common [6]. By harvesting even small amounts of ambient energy from relatively predictable sources like solar, a CRFID can take greater risks because the probability of a complete loss of state is much lower. For instance, it may be sufficient for a hybrid CRFID to checkpoint only after major milestones such as completing a computation.

Looking forward, emerging nonvolatile memory technologies may fundamentally change the way that CRFIDs deal with these challenges. For example, MRAM is nonvolatile and features fast read and write times. These new technologies could potentially eliminate the need for new processor architectures to separate volatile and nonvolatile memories, thus allowing data to be checkpointed in place rather than wasting time and energy transferring data to flash. It is not clear when this technology will be available on small microcontrollers.

4. RELATED WORK

Energy management for harvesting-based sensor networks has been studied in the past. Moser et al. [4] present optimal scheduling algorithms for harvesting networks that must meet deadlines, but the system requires hard deadlines, inter-node communication, and observation of energy availability over long time scales. Kansal et al. [2] focus on design motivated by modeling of energy source variations over time, which again requires long-term observation not possible with CRFIDs.

Several operating systems and languages maximize energy efficiency in sensor networks. TinyOS [3] strives to support effective energy management via aggressive duty cycling by the scheduler and exposure of power management APIs, but TinyOS is a full operating system that is not explicitly aware of energy and does not adapt, leaving this to the application programmer. The Eon language and runtime system [9] is similar in spirit to our work because it adapts based on energy-awareness, but is designed to work with platforms less constrained than CRFIDs and within the longer timescales that these battery-powered platforms support.

The viability of various energy harvesting sources for computation and sensing has been considered many times in the past [5]. Intel has demonstrated a WISP retrofitted with a directional TV antenna capable of harvesting energy from a TV transmitter over two miles away when positioned carefully [7]. The energy, however, was used to power a static load (small thermometer with LCD) rather than a WISP or other computation device.

As the first example of a CRFID, Intel's WISP has defined the class of devices [8]. Yeager et al. propose the use of supercapacitors to extend the fleeting lifetime of the WISP given a full charge [10] but do not examine energy conservation techniques beyond duty cycling.

5. CONCLUSION

Hybrid energy harvesting enables CRFIDs to overcome the challenges to autonomy that currently limit their usefulness in many applications. Moreover, our preliminary experiments demonstrate that the addition of a second harvesting circuit to the WISP yields three-fold improvements in read rate and two-fold improvements in read range. These results are surprising to the WISP designers because conventional wisdom regarding the Friis transmission equation would indicate that additional power on a CRFID would not affect the quality of backscatter communication. However, the hybrid energy allows a CRFID to overcome the large startup overhead to more quickly reach the nominal operating voltage. The hybrid approach also allows the WISP to perform computation, sensing, and storage independent of the RFID reader infrastructure.

CRFIDs require a different approach to energy management from battery-powered devices because of their low harvesting rate and extremely constrained energy storage. Our design hints intend to enable more effective energy management for CRFIDs in light of their particular limitations.

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