Revisiting Smart Dust with RFID Sensor Networks

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Abstract

We argue that sensing and computation platforms that leverage RFID technology can realize “smart-dust” applications that have eluded the sensor network community. RFID sensor networks (RSNs), which consist of RFID readers and RFID sensor nodes (WISPs), extend RFID to include sensing and bring the advantages of small, inexpensive and long-lived RFID tags to wireless sensor networks. We describe sample applications suited to the space between existing sensor networks and RFID. We highlight the research challenges in realizing RSNs such as the use of intermittent power and RFID protocols suited to sensor queries.

1 Introduction

In the late 1990s, the vision of “smart-dust” was articulated by the research community. This vision was predicated on advances in microelectronics, wireless communications, and microfabricated (MEMS) sensing that were enabling computing platforms of rapidly diminishing size. The early proponents imagined devices one cubic millimeter in size with capabilities sufficient to power themselves, sense the environment, perform computation, and communicate wirelessly [7]. Large-scale deployments of such devices would enable a wide range of applications such as dense environmental monitoring, sensor rich home automation and smart environments, and self-identification and context awareness for everyday objects.

The past decade has seen significant effort and progress towards the original motivating applications. In particular, wireless sensor networks (WSNs) based on “mote” sensing platforms have been applied to many real-world problems. Remote monitoring applications have sensed animal behavior and habitat, structural integrity of bridges, volcanic activity, and forest fire danger [5], to name only a few successes. These networks leveraged the relatively small form-factor (approximately 1” x 2”) of motes and their multihop wireless communication to provide dense sensing in difficult environments. Due to their low power design and careful networking protocols these sensor networks had lifetimes measured in weeks or months, which was generally sufficient for the applications.

Despite this success, WSNs have fallen short of the original vision of smart-dust. They have not led to an approximation of sensing embedded in the fabric of everyday life, where walls, clothes, products, and personal items are all equipped with networked sensors. For this manner of deployment, truly unobtrusive sensing devices are necessary. The size and finite lifetime of motes make them unsuitable for these applications.

We argue in this paper that Radio Frequency Identification (RFID) technology has a number of key attributes that make it attractive for smart-dust applications. Passive UHF RFID already allows inexpensive tags to be remotely powered and interrogated for identifiers and other information at a range of more than 30 feet. The tags can be small as they are powered by the RF signal transmitted from a reader rather than an onboard battery; aside from their paper thin antennas, RFID tags are approximately one cubic millimeter in size. Moreover, their lifetime can be measured in decades as they are reliable and have no power source which can be exhausted. These advantages have resulted in the widespread deployment of RFID for industrial supply-chain applications such as tracking pallets and individual items. However, RFID technology is limited to only identifying and inventorying items in a given space.

The RFID Sensor Networks (RSNs) we advocate in this paper extend RFID beyond simple identification to in-depth sensing. This combines the advantages of RFID technology with those of wireless sensor networks. In our previous work, we have demonstrated the technical feasibility of building small, battery-free devices that use the RFID PHY and MAC layer to power themselves, sense, compute, and communicate; we refer to these devices as Wireless Identification and Sensing Platforms (WISPs)[12, 13]. While other research efforts such as [3] have combined RFID with sensing, to the best of our knowledge, the Intel WISP is the only RFID sensor node with computational capabilities and that operates in the long range UHF band.

While the feasibility of WISPs has been established by this earlier work, how to harness many such devices to create RSNs is an open question. An RFID sensor net-

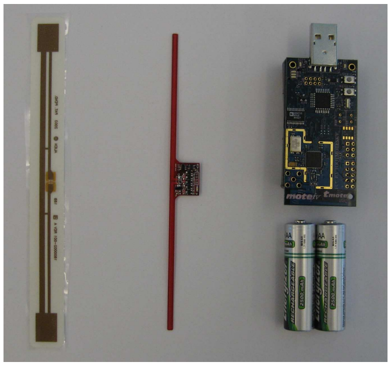

Figure 1: Commercial UHF RFID tag, Accelerometer WISP, Telos mote with batteries

work consists of multiple WISPs and one or more readers. Consequently, realizing full-scale RSNs will require development at both the WISP and the reader, as new protocols and techniques must be developed unlike those of either RFID or WSNs.

The focus of this paper is the applications that RSNs enable and the systems challenges that must be overcome for these to be realized. As the traditional RFID usage model is very different from that of WSNs, RSNs face substantial challenges when trying to integrate the two technologies. For example, unlike WSNs, RSNs must cope with intermittent power and unlike RFID must support sensor queries rather than simply identification.

2 From Motes and RFID to RSNs

Two technologies have been widely used to realize real-world monitoring applications: wireless sensor networks via motes, and RFID via standard tags and readers. We describe and contrast each technology and then present their combination (Table 1) as RFID sensor networks (RSNs). We use prior work on the WISP [12, 13] to demonstrate the technical feasibility of this combination. Representative devices for the three technologies are show in Figure 1.

2.1 Wireless Sensor Networks (Motes)

Currently, most WSN research is based on the Telos mote [10], which is a battery powered computing platform that uses an integrated 802.15.4 radio for communication. These motes are typically programmed to organize into ad-hoc networks [15] and transmit sensor data across multiple hops to a collection point. To extend network lifetime, motes duty cycle their CPU and radio (e.g., with low-power listening [9]), waking up intermittently to sense and communicate. With a duty cycle of 1%, motes can have a lifetime of up to three years before the batteries are exhausted.

Using multihop communication, WSNs can sense over great distances, which has made them idea for a wide range of applications. However, the large size of the mote and its finite lifetime makes it unsuitable for applications where sensing must be embedded in small objects, or in inaccessible locations where batteries cannot be replaced.

2.2 RFID

While there are a number of different RFID specifications, that of greatest interest for sensing applications is the EPCglobal Class-1 Generation-2 (C1G2) protocol [4], as it is designed for long-range operation. The C1G2 standard defines communication between RFID readers and passive tags in the 900 MHz Ultra-High Frequency (UHF) band, and has a maximum range of approximately 30 feet. A reader transmits information to a tag by modulating an RF signal, and the tag receives both down-link information and the entirety of its operating energy from this RF signal. For up-link communication, the reader transmits a continuous RF wave (CW) and the tag modulates the reflection coefficient of its antenna. By detecting the variation in the reflected CW, the reader is able to decode the tag response. This is referred to as "backscattering," and requires that a tag be within range of a powered reader.

The MAC protocol for C1G2 systems is based on Framed Slotted Aloha [11], where each frame has a number of slots and each tag will reply in one randomly selected slot per frame. Before beginning a frame, a reader can transmit a *Select* command to reduce the number of active tags; only tags with ID's (or memory locations) that match an included bit mask will respond in the subsequent round. After a tag replies, the reader can choose to *singulate* the tag, or communicate with it directly, and read and write values to tag memory. These mechanisms enable rapid tag identification and unicast read and write.

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. As they are powered by the reader, the device itself can be very small, though the antenna requires additional area. As the antenna is flexible and paper thin, their small size means they can be affixed to virtually any object to be identified However, RFID tags provide no general purpose computing or sensing capabilities.

2.3 RFID sensor networks (WISPs + readers)

We define RFID sensor networks (RSNs) to consist of small, RFID-based sensing and computing devices (WISPs), and RFID readers that are part of the infrastructure and provide operating power. RSNs bring the advantages of RFID technology to wireless sensor networks. While we do not expect them to replace WSNs for all applications, they do open up new application spaces where small form-factor, long-lived, or inaccessible devices are paramount. Our hope is that they will

	CPU	Sensing	Communication	Range	Power	Lifetime	Size (inches)
WSN (Mote)	Yes	Yes	peer-to-peer	Any	battery	< 3 yrs	3.0 x 1.3 x .82 (2.16 in^3)
RFID tag	No	No	asymmetric	30 ft	harvested	indefinite	6.1 x 0.7 x .02 (.08 in^3)
RSN (WISP)	Yes	Yes	asymmetric	10 ft	harvested	indefinite	5.5 x 0.5 x .10 (.60 in^3)

Table 1: Comparison of Technologies

elegantly solve many sensor network applications, e.g., home sensing and factory automation where installing or carrying readers is feasible.

Prior work at Intel Research demonstrates that WISPs can be built today. The most recent Intel WISP is a wireless, battery-free platform for sensing and computation that is powered and read by a standards-compliant UHF RFID reader at a range of up to 10 feet. It 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 WISP includes 32K of flash program space, an accelerometer, temperature sensor, and 8K serial flash. Small header pins expose microcontroller ports for expansion daughter boards, external sensors and peripherals.

The Intel WISP has been used to implement a variety of demonstration applications that read data from a single sensor unit. These include the first accelerometer to be powered and read wirelessly in the UHF band, and also the first UHF powered-and-read strain gage [17]. Even without its sensing capabilities, the Intel WISP can be used as an open and programmable RFID tag: the RC5 encryption algorithm was implemented on the Intel WISP [2]. We believe this is the first implementation of a strong cryptographic algorithm on a UHF tag.

3 Example Applications

RFID sensor networks have broad applicability wherever sensing, small form factor, embeddability, longevity, and low maintenance are desired and fixed or mobile readers are feasible. This section highlights applications within this space and some of the key design considerations.

3.1 Blood

Blood transfusions save lives, replacing blood lost during surgery, illness, or trauma. After donation, blood is bagged and refrigerated between 1° and 6° C and has a shelf life of about 35 to 42 days. Refrigerators used to store blood are monitored for outages and temperature fluctuations, and collection dates are recorded on blood bags. However, the temperature of the bag itself is rarely monitored with any regularity. This makes it difficult to determine if a given bag was warmed to unsafe levels, such as if it is near the front of the refrigerator and the door is often opened. Additionally, it is difficult or impossible to gauge exposure during transport from a donor to a bank, between banks, and ultimately to a patient.

WISPs with temperature sensors could be attached directly to individual blood bags and queried for their measurements. Such sensors must be small (one could imagine affixing sensors with something like a price tag gun), and inexpensive to the point of being disposable.

To understand the challenges in building such an application, an Intel WISP was attached to a container of milk (a suitable and widely available approximation of a bag of blood), and its temperature was monitored over the course of 24 hours [16]. For this study, a storage capacitor (roughly the size of a pea) was attached to the WISP to log sensor data for up to a day when out of range of a reader.

3.2 Brains

Research in neuroscience has explored using neural sensors for controlling prosthetic limbs [14]. Sensors placed outside the skull can capture neural activity, but the signals are too coarse-grained and noisy to be effective. With surgery, sensors can be placed directly on the brain, resulting in much higher resolution and finer control of the limb. Using conventional technologies (e.g., motes) presents difficulties with respect to power because batteries need to be replaced via invasive surgical procedures, as is the case with pacemakers.

An RFID sensor network is well suited to this application. A patient would have WISPs equipped with neural probes placed inside the skull. These could then draw power from and communicate with a device outside the body, e.g., an RFID reader worn as a cap, bracelet, or belt. We have completed initial studies that show the feasibility of integrating neural sensors with the WISP [6].

3.3 The Elderly

Providing care for the elderly is one of the largest healthcare costs facing us today, particularly as the “baby boomer” generation ages. Keeping people in their homes for as long as possible significantly reduces these costs and increases quality of life. The difficulty with this is in detecting and reacting to emergencies, such as the patient falling or forgetting to take critical medication. Currently, families have no choice but to hire costly support personnel to regularly check-in on their loved ones.

Traditional RFID has been explored to help monitor the behavior of the elderly. For example, by having the patient wear a short range RFID reader bracelet and placing RFID tags on a toothbrush, toothpaste, and faucet, software can infer that an elderly person is brushing her teeth when these tags are read in succession [8]. Such fine-grained sensing requires very small devices, and is simpler and more respecting of privacy than competing approaches using computer vision, where video of the person is continuously recorded and analyzed.

Adding sensing (e.g., an accelerometer) to long range RFID tags would have several key advantages. Rather than requiring a person to wear a short-range reader, which can be taken off, a few long-range readers could be placed in the home and behavior could be determined via direct communication with the objects that are being interacted with. This explicit information would be more accurate in detecting behavior than inference based only on object identifiers.

RSNs are an appropriate solution for the above applications and those like them. Our initial studies using the WISP show the potential of existing RFID sensing devices for use in such applications. However, these studies involved only a single WISP. Combining many such devices into a full RSN will require further research.

4 Challenges

RSNs combine the technology of RFID and sensing with the usage models of sensor networks. At the device level, the WISP shows that it is feasible to combine sensing with RFID. However, at the systems level, challenges arise due to the mismatch between the RFID usage model and that of wireless sensor networks. We detail several challenges in this section.

4.1 Intermittent Power

RFID readers provide an unpredictable and intermittent source of power. This makes it difficult for WISPs to assure that RSN tasks will be run to completion. WISPs are powered only when in range of a transmitting RFID reader and, for regulatory and other reasons, readers do not transmit a signal continuously. Instead, they transmit power for a brief period before changing channels or entirely powering down. For standard RFID tags where the task is simply to transmit the identifier, this style of communication is sufficient. However, it is a poor fit for RSN tasks that span many RFID commands.

The WISP harvests energy from a reader and stores this energy in a capacitor. When enough energy is harvested, the WISP powers up and can begin sensing and communicating. However, sensing and communication drain power from the WISP. This can result in the WISP losing power in the middle of an operation depending on the task and the reader behavior. A further complication is that receiving, transmitting, performing computation, and reading/writing to memory all consume different amounts of energy.

To run tasks to completion, WISPs will require support for intermittently powered operation. They must be able to estimate the energy required to complete a task, perhaps based on task profiling or energy budgets, and compare it with estimated reserves. To work well in this regime, RSN devices may also need to cooperate with RFID readers for power management. This would involve signaling by either the reader, of its intended transmission time, or by the WISP, of its needs. Even with signaling, it will be difficult to predict power expectations because the rate at which energy is harvested depends on the frequency of the reader and the proximity of the device to the reader, both of which will change over time. Thus, to increase the kinds of tasks that could be supported, large tasks might need to be split into smaller, restartable stages; intermediate results between the stages could be maintained in device storage (flash or RAM) or be offloaded to the reader.

To extend functionality when away from a reader, one approach would be to provide a small amount of energy storage on the device, e.g., a capacitor, and store excess energy when close to an active reader. This storage capacitor would be small relative to a battery, because it would be intended only for short term usage and is wirelessly recharged over time. The Data Logger WISP used for the milk carton study takes this approach, using a super-capacitor that, when fully charged, sustains low duty-cycle operation for more than a day. The type of tasks that this WISP enables would be limited, due to energy requirements, and the period of functionality would be limited due to leakage. Additionally, unpowered operation would likely stress tradeoffs between stages. For example, writing to flash is significantly more energy intensive than computing with RAM but preserves valuable data for later use.

4.2 Asymmetric Sensing Protocols

The communication paradigm of RFID results in systems that are limited by up-link bandwidth. When the data of interest is simply each tag's identity, this constraint is not a problem. However, it makes it difficult to develop efficient protocols for gathering sensor data that changes over time. In WSNs, nodes are peers in terms of the physical and link layers of their communication, e.g., each mote has an 802.15.4 radio capable of sending and receiving transmissions with other nodes that are in range. In contrast, because they draw on RFID, RSN nodes are highly asymmetric in terms of their communication abilities. With RFID, readers are able to transmit messages to all tags and tags can transmit messages to the reader. However, tags can do so only when the reader initiates communication, and tags cannot communicate directly with each other even when powered by the reader.

These differences complicate the design of protocols for gathering sensor data. Currently, WISPs with new sensor data must wait until they are interrogated by a reader. This increases the likelihood of many devices wanting to use the bandwidth limited channel at the same time. Techniques to perform data pre-processing within the network (on each RSN device) could help to some extent. However, the standard RFID strategy of identifying and then communicating with each device is wasteful as only some devices would have relevant data – a more dynamic strategy based on the value of the sensor data would be more effective.

Consider the eldercare application. A reader might have hundreds of accelerometer WISPs in its field of view. Because all the WISPs share a single reader channel, the update rate per tag would be very low if every tag were simply queried for sensor data sequentially. However, at any given moment, only a few objects would typically be in motion (and therefore producing non-trivial accelerometer sensor values). Furthermore, the set of objects that are moving would change dynamically, as objects are put down and picked up. One might want a protocol which gives priority to the most active objects, politely "yielding" to new objects when they start to move.

Existing RFID solutions do not support anything like this functionality. As a first step, one could have WISPs with sensor activity below a threshold not respond to the reader. But an appropriate threshold level might depend on what is occurring in the room, and such a simple scheme would not support the "polite yielding" described above.

For another example of what RSN protocols might be asked to do, consider the blood application. When many blood bags are read simultaneously, one might want to interrogate the bags with the largest temperature excursions first. But since the distribution of temperature excursions would not be known a priori by the reader, the protocol would need to (implicitly) estimate this information. It might for example ask if any WISP has a larger temperature excursion than E. If no device responds, the E response threshold could be repeatedly halved until the appropriate scale is found. The key requirement would be to estimate an aggregate property of the data without exhaustively collecting that data. Finally, RSN protocols might be power aware as well. A WISP that was about to lose power might be given priority over those with ample power.

As the WISP has limited program space, it may not be possible to program a WISP such that it will be well matched to all possible application scenarios. For example, WISPs may need different protocols for different deployments, and these needs may change over time. However, the communication model of passive RFID means that the reader can have a large degree of control over what code is loaded and executed on the WISPs at any point in time.

In contrast to mote message reception, which consumes energy from small onboard batteries, WISP message reception is powered entirely by the reader. Thus, frequent and large code transfers are feasible, which would allow for the complete retasking of WISPs with costs in terms of latency only. Moreover, since downlink communication is cheap when in range of the reader, WISPs might not need to be as "smart" as motes. Rather than requiring WISPs to interpret queries, readers could tell WISPs exactly what to do, down to the instruction level.

To fully exploit the potential of RSNs, new tools must be developed. As a first step, we are developing an RFID reader platform based on the Universal Software Radio Peripheral (USRP). This platform, when used in conjunction with the WISP, would allow for the development of new protocols at both the MAC and PHY layers. Thus far we have used it for monitoring RFID systems [1].

4.3 Repurposing C1G2

There would be substantial practical benefit to realizing RSN protocols using the primitives of the C1G2 standard: Commercial off-the-shelf readers could be used for RSN research and deployment, and WISPs would interoperate with ordinary (non-sensing) tags. However, the extent to which RSN protocols could be implemented within the C1G2 standard is an open research question. Additionally, there is the practical consideration of commercial readers not exposing low-level functionality and not implementing the complete C1G2 specification. Because of this, even RSN protocols built on top of the C1G2 specification might not be implementable using standard readers.

Our experience with the Intel WISP suggests that basic RSN applications could be approximated using standard C1G2 readers. To read sensor data from a C1G2 WISP, the device would first be *singulated*, at which point a temporary *handle* would be requested from the tag. A reader could then use this handle to address the device and read sensor data from pre-defined memory locations. However, the handle would persist only until the reader singulates another tag or the tag loses power. Thus, reading from more than one WISP would incur substantial protocol overhead due to singulation and handle management. Consequently, simple use of the existing C1G2 protocol could provide some level of sensing functionality, but at a significant cost in terms of efficiency.

Along with reading sensor data, the C1G2 protocol could support basic sensor queries using the *Select* command. If the reader knows that a sensor value is written to a particular memory location, it could issue a *Select* command with a mask which matches that location for sensor values over a given threshold. Consequently, only WISPs with sensor values over that threshold would reply during the next frame. More generally, the *Select* command could be used as a general purpose broadcast channel. The bit mask in the command could be repurposed and interpreted, in the most general case, as opcodes and data. As multiple *Selects* could be sent before each frame, complex tasking and querying could be achieved in this manner.

The above mechanisms show that there is potential for using the C1G2 standard to implement RSN protocols. This would have the advantage of being implementable using current reader technology, given a reader that is sufficiently programmable. However, these mechanisms may prove too inefficient or may simply be poorly matched to many applications. Further experimentation is needed.

5 Conclusion

By exploiting RFID technology, we believe that we can expand the application space of wireless sensor networks to ubiquitous, embedded sensing tasks. We have sketched sample sensor network applications in the space between traditional mote networks and RFID for supply-chain monitoring. We have described key systems and networking challenges related to intermittent power and RSN protocols for sensor queries. We expect RSNs to be a fruitful new space for networking and systems research, as there is significant work that must be done to translate the capabilities of the WISP into full-fledged RSNs.

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