# Infofield:

## An Aura Recognizing Digital Information of Everyday Environment

by

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Bachelor of Science in Electrical Engineering
Korea Advanced Institute of Science and Technology, 2006

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements of the degree of
Master of Science
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY



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## Abstract

Many ubiquitous computing scenarios are enabled by the ability to detect and identify objects in a user's environment, and recently Radio Frequency Identification (RFID) has been considered an affordable technology for providing such ability. However, RFID approaches have been flawed: when they operate at long range, they fail to provide adequate context as to which tagged objects are the subject of the user's interest; and when tuned for short range operation, they require the user to explicitly scan the tagged object. In addition, the knowledge gained from the user interacting with the object is limited to identification.

This thesis proposes an ambient metaphor for detecting daily environments suitable for the upcoming far-field UHF RFID infrastructure. A user carries a mobile RFID reader, which creates a sphere of detection field to monitor RFID tags surrounding the user. The reader silently monitors the objects and functions as an agent that supports the user's consciousness of events happening outside of the user's attention. With sensor-enhanced RFID tags, our system does not limit itself to identification, but also provides the status of the corresponding item. The data from the sensors are used to distinguish a tag in a multiple tag environment and to describe the interactions between the user and the host object. This improves the selectivity and the context-awareness of the system.

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**Infofield:**

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# Chapter 1

# Introduction

## 1.1 Motivation

***A proactive digital environment***

What if your mobile phone could automatically detect what's around you, memorize what objects you have used throughout the day, and even warn you if your keys are left behind?

We glance through our surroundings looking for people, places, or things that interest us. Once something catches our eye, we then focus on it for further information. Our eyes effectively focus in and out, catching the details of our environment.

While we can still read and memorize what we see, retrieving and recording the information has been much easier with the aid of digital devices and digital networks. Barcodes, which store a code visible to an optical reader, can be accessed by taking a photo of the barcode with your mobile phone [1]. The phone then shows the linked data to which the barcode points, which could be text, photos or video clips that are stored on the Web. Also, Radio Frequency IDentification (RFID) has been used as an affordable solution to tag and augment digital contents into the physical world. RFID tags are read when they fall in the RFID reader's affective read range. Being free of line-of-sight limitation, the tag can be implanted under the surface of an object, making the tagging invisible to the users. Earlier research [2] [3] [4] provided human-computer interaction (HCI) models using barcodes or RFID tags to retrieve and remember digital contents from physical objects.

These scenarios promise a stable identification, yet these systems are limited to one-to-one interaction scenarios that ask the user to explicitly aim or point at the object with a device in order to read out the information in the tag. Most interactions are initiated with user intention, as the user has to know in advance where to point in order to read a tag. Therefore, these systems help the users to get more information about what they want to know, but not about what they are not aware of at the moment.

Many recommendation scenarios are based on databases and search tools. The systems have access to databases and they filter information according to the user's preferences and present the matching data to their users. Like Amazon.com, the portal site tracks what you browsed and bought and recommends further items that may be of interest. The system tracks purchased items, when they were bought, and how much they cost, and presents a well-organized report to the users. The system even sends an email to you when an item you have linked to on a wish list drops in price. This reduces the overhead of information to which a user will be exposed. With the growth of mobile handsets and broadband networks, people can access the Internet wherever they move; as an immense database of almost everything we buy off the store is already available on the Web, many appealing recommendation scenarios in the physical space can be enabled if our handsets were aware of the objects around us.

We designed a platform, the Infofield, which performs an ambient monitoring of the user's surroundings. Similar to radar, this system creates a field that detects any objects with RFID tags that fall within its range. The ideal shape of this field will be spherical; however, the shape is affected by the surrounding RF environment. The range of the field could be set according to the users' preferences on how far they care to be informed. When a tag moves in and out of the field, the system generates an event to alert the user when a preferable object appears in the field or when the user drops an item. The system monitors all RFID-tagged objects inside the spherical field, and decides what objects the user is mostly interested in via a rating metaphor. The rating system is based on the sensor values accumulated while the user interacts with the item. In various objects, each embedded tag would sense the factors that best describe the status of their hosted item.

To demonstrate the scenario, we have also implemented sensor-enhanced RFID tags, the SensTags.

***The World of RFID***

We used RFID technology for Infofield to propose a real, applicable system. While using other technologies like Bluetooth or Zigbee would be a painless approach to demonstrate a similar concept, it is hard to imagine that such costly platforms would be augmented into our daily objects.

The Infofield system uses the Electronic Product Code Class 1 Generation 1 (EPC C1 G1) protocol. This protocol, based on the far-field Ultra High Frequency (UHF) RFID technology, has become an appealing solution in supply-chain management, successively increasing its numbers in the market. This technology has become an attractive solution for connecting everyday objects to the ubiquitous network, especially for its robustness and cost, given that RFID tags will be deployed by the need of the supply chain. Finding an effective usage of these RFID tags beyond the supply chain will accelerate the migration from barcodes to RFIDs.

## 1.2 Scope of this thesis

In this document, we explore the use of wearable RFID systems to leverage the upcoming UHF RFID infrastructure and create a proactive environment.

The main focus of this work is to implement a new system, Infofield, which comprises a mobile RFID reader and programmable tags. We have modified a commercially available RFID reader to fit into a mobile scenario, and analyze the factors that should be accounted for far better performances. We have also built sensor-embedded RFID emulators to monitor the environment and the status of the hosted item. Although many other sensor network systems allow better sampling of the users' actions than the Infofield system, they cannot be deployed in every object due to cost, size, and battery management. The unique contribution of our work is that our system can be absorbed into an existing infrastructure. The programmable tags we present here would be battery powered for demonstrations, but our design and the sensor selections are bounded to meet the power level of a passive UHF RFID tag.

With this system, we propose a novel approach of using a preexisting UHF system: instead of deploying RFID readers which track the users, the users carry mobile RFID readers to scan their environment. Other UHF RFID systems have been applied in supply chains, where there is a grid of readers to monitor the flow of the tag. Similarly, previous approaches of utilizing distributed RFID tags were not much different from the supply-chain system; in those approaches, a number of RFID readers cover a space, monitoring the tags flowing around the area. The trails of each tag are centralized to a system that analyzes the correlation of the tags to infer the activities of the user. In this system, the users are also considered as a tagged object. Instead, our system enables a personal monitoring of one's surroundings and describes the interactions in a user-centric way. By having the control of its own data, the Infofield promises better privacy.

Moreover, we try to solve the singulation problem in a one-to-multiple interaction scenario. In a comparatively long-range identification system such as Bluetooth, multiple devices are detected over a distance, but each device provides a display or other feedback to the users so that they can identify it. However, adding an output device on a passive RFID tag is impractical due to the power issues. Instead, we add low-power sensors on RFID tags so that the system can tell which tag is interacting with the user by reading the change of the sensor values from the tags. We use the sensor values from the tags to provide more information about the status and the environment of the hosted items. The status information from each item can be used to detect whether the user is interacting with the item and also infer some simple activity such as 'the person is opening a box,' 'holding a book,' or 'flipping a page.' The tangibility [5] of the system could be used as an interface to manipulate other information.

## 1.3 Thesis structure

The following parts of the thesis report on the work in the order outlined here. Chapter 2 contains a detailed discussion of technologies and research that have been previously explored. Chapter 3 provides a description of the Infofield's hardware system and firmware. Chapter 4 illustrates the user interface of the system, stating how the tags can be augmented into our daily objects and what could be visualized to the user. Chapter 5 discusses the lab performance of the system, its analysis, and the result of the preliminary user evaluations. Health and privacy issues will also be discussed in this chapter. Finally in, Chapter 6, we state our contributions and future work.

# Chapter 2

# Background

## 2.1 Brief Introduction to RFID

Radio Frequency Identification (RFID) is a powerful tool for pervasive computing. It allows objects to be easily tagged so that the ubiquitous computing infrastructure can identify and track objects in the physical environment. RFID tags are comprised of a circuit that stores a unique number and an antenna to harvest power and communicate wirelessly to the RFID reader. Passive (power harvesting) tags are simple and low cost [6] since they do not require batteries. The use of RFID in commercial settings promises enhanced visibility in the supply chain, theft prevention, and counterfeit detection. Encouraged by such potential benefits, the supply chain has started to increase the RFID tagging of goods at the time of manufacturing.

The characteristics of an RFID system vary by which frequency the system uses. For instance, near-field RFIDs, which operate below 13.56MHz, use inductive coupling and limit their read range to a few inches in most applications. These types of RFIDs are widely used in security cards, public transportation cards, and most applications of HCI research mentioned on this paper.

Far-field RFID or Ultra High Frequency (UHF) RFID works at approximately 900MHz [7] (varies due to different regulation among countries). The two distinguishing characteristics of UHF RFID compared to lower frequency RFIDs are the read distance and the multi-tag recognition feature. Theoretically, the range of any RFID system can be increased by transmitting higher power through the antenna, but UHF RFID systems are more adaptive to the 1~10 meter range than the lower frequency systems. Lower-frequency RFIDs usually do not support anti-collision for multiple tag reads, but UHF RFID systems have a mandatory anti-collision feature to read multiple tags within the sensing field. While the near field RFID tags are used in security access or payment systems, far- field RFIDs are the technology in demand in the supply chain for its read range, cost, and multi-tag scanning feature.

## 2.2 Other systems for ubiquitous computing

### 2.2.1 Computer vision

Computer vision uses optical sensors to see most of – or even beyond – the images that our eyes see; it tries to detect the object by analyzing the appearance, therefore requiring no artificial tagging, which makes the system affordable and widely applicable. The SenseCam [8] project uses an automated camera to capture everyday life and let people record their experiences without having to operate the recording equipment. The series of snapshots from the SenseCam is uploaded into a MyLifeBits [8] repository, where users can retrieve, browse, and organize their memories. However, in most cases including the SenseCam, the computers can hardly extract information out of an image without any digitized patterns on the image. The performance of computer vision has a great potential, but is not yet robust enough for general use.

### 2.2.2 Barcodes

Barcodes are patterns of distinguishable lines or spots (for 2 dimensional barcodes) that can be detected by using optical arrays or cameras. Barcodes have been widely adopted as the Universal Product Code (UPC). The length of data stored on a barcode is limited by its size, but by using barcodes as a pointer to a data stored in a network, the overall data space becomes unlimited. Today, most mobile phones can be enabled to decode simple barcodes with their existing cameras. For example, the use of QR codes [2] in conjunction with mobile phones is widespread in Japan. Yet, barcodes require a strict positioning of an optical device to a tag in order to initiate the process of retrieving digital information from a physical object.

### 2.2.3 Sensor module

Many applications use sensor networks for environmental detection [9][10]. Each node is basically a small battery powered computer with wireless communication using infrared (IR) or a radio (e.g., Bluetooth). The functions each node offers are scalable, depending on the complexity that the platform requires. Also, these systems provide long-range (~10m) connectivity and could power feedback indicators to the users to notify the location of the nodes. Applications using sensor networks could be easily demonstrated, but were not as applicable to a real-world scenario due to the cost, size, and the battery lifetime of the sensor module.

## 2.3 Related works

### 2.3.1 Wearable RFID readers

Schmidt et al. [2] demonstrated one of the earliest wearable RFID systems, having only the antenna embedded in a work glove and the rest of the system worn on the user's belt. The authors used the tag as a real-world bookmark, each tag having a unique URL to a Web page, and discussed how RFID readers can be used as an input in a human computer interaction design. IGlove [3], developed by Intel research, minimized the bulky system onto a single device and made the system more portable. The glove readers by Schmidt and Intel research were both tuned to a short range, so that the readers could only detect the tag within the glove's grasp. The data were used to infer the user's daily activities [11]. The iBracelet [12] , also from Intel research, is a wristband form of the iGlove. With an increased reading range of 10cm, the iBracelet approximately covered the area where the user would grasp an item. ReachMedia [13], developed by Feldman et al., is a system that uses gesture input in conjunction with a tag's ID to navigate the data to which the tag links. The system uses a wristband embedded with an RFID reader and accelerometers to measure the movement of the wrist. The ID of the tag is transmitted to the host computer as the user holds the host item, and with gesture commands the user can select the information associated with the tag.

The Near Field Communication (NFC) integrated mobile phone is also a relevant point of comparison. The NFC is a wireless communication protocol operating on 13.56MHz with the same mechanism as a high-frequency RFID system. The NFC reader has been embedded into Nokia mobile phones, enabling short-range interactions with consumer electronics, objects, and location mappings [14]. The NFC reader and the Infofield share a common metaphor of using a mobile phone to access the digital tags in the physical world. What is appealing about this standard is that the tags are opened for the end users to use their NFC-enabled phone to read and program the tag.

In the listed example, researchers have addressed the usages of RFID in direct tagging or single tagging scenarios, yet the usage in the latest long-range RFID have been less fully explored. The UHF RFID system is optimized to read a large space and track multiple tags at once, so a different metaphor should be provided for effective use of the system.

Galatea [15] is also a very relevant system to the Infofield. Galatea uses a cell phone to search tagged books in physical space using Bluetooth channels. The tag-augmented books contain Bluetooth modules, and therefore have a typical Bluetooth communication range of 10 meters, which is long enough to cover a room. In addition to the range, the key feature of Galatea is the LED that blinks to the users. FindIT Flashlight [16] is a comparable system to Galatea, as the tags in the FindIT system also helps the user search items by providing feedback with LEDs. But instead of using the RF field, FindIT is optically-interrogated with its Flashlight. These systems are much more effective in terms of the coverage and the ease of locating an item than what our Infofield presents, but the technology apparently lacks practicality in augmenting it into every book.

### 2.3.2 Previous usage of UHF RFID system

Welbourne and his colleagues [17] explored the use of a UHF RFID system in a public place by deploying hundreds of readers in a building and tagging thousands of objects with the tag. Their goal was to uncover the issues of pervasive RFID deployments and devise techniques for addressing these issues in a common place. Their paper approaches the issues in a scenario where a central server monitors the flow of objects and people. The data from the system is space-oriented, which shows whether an object was seen at a certain location and time. The system infers the interaction among objects by correlating their trails, but in general, fails to deliver detailed information about interactions among the objects.

User-oriented data would best describe the events between people and objects. By changing the position of readers and tags – tags on places and mobile readers on users – we could get a richer context out of a system. Also, adopting an infrastructure similar to what is used in the supply chain limits the ability to provide a privacy-friendly service. The remote detection of the long-range RFID systems provokes privacy concerns [12]. In the system I propose, the user controls the reader's data in the platform, resulting better security.

## 2.4 The Infofield system

Infofield monitors RFID tags to support the users' consciousness of events happening outside their attention. Compared to the UHF RFID systems of the past, which used fixed readers to scan moving RFID tags in the area, Infofield takes an opposite approach: we move the readers inside a pool of tags. By reading the environment instead of being read by them, users have control over their own data, ensuring better privacy. We take this new approach using a long-range, wearable RFID reader and sensor-enhanced RFID tag to measure the interaction between human and objects.

UHF RFID systems have an advantage in monitoring multiple tags from a distance. This system suits the application in a supply chain where the reader has to detect any tag that passes its reading range. We are also using this feature of the system to enable ambient monitoring of the users' surroundings; however, as we use RFID tags for everyday interactions, the system faces the singulation problem – to read a specific tag out of a number of present tags – which was not an issue for the original supply-chain usage.

Infofield suggests how sensing capabilities on RFID tags would help to reduce the singulation issue. Our programmable RFID tag measures the status of the host item to distinguish itself in a multiple-tag environment, and to describe the interactions between the user and the host item. This improves both the selectivity and the context-awareness of the system.

In our scenario, the user carries a mobile device that captures every surrounding physical object that contains RFID tag without distracting the user. The device creates a detection field with a range slightly longer than the space one's body could reach. The reader easily senses passive tags on buildings, rooms, and furniture and uses the data to locate the user on a map, enabling location-aware services. Also, the reader will be able to tell what the user is carries, what objects the user encounters, what the user leaves behind, what chair the user sat on, and so forth. The detection is not limited to a user's right hand, nor does it requires physical intentions.

# Chapter 3

# Hardware Platform

## 3.1 Overview

The Infofield system consists of three main devices:

1. SensTags (RFID tags)
2. ThingMagic Mercury 4e (RFID reader)
3. Nokia N800 (mobile computer)

To demonstrate the RFID system, we have implemented the RFID tags and the reader. The transponder is called SensTag, which is a UHF RFID emulator with a general-purpose microcomputer. This platform is based on our previous platform, the OpenTag.

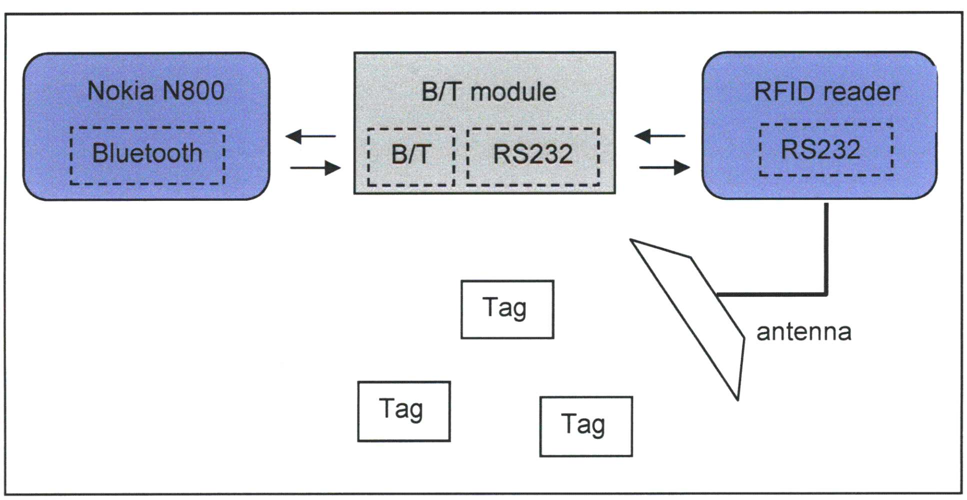


**Figure 1: The Infofield system.**

While technologies like WiFi and Bluetooth are now integrated into compact devices such as cell phones, the demand of a compact UHF RFID reader is a recent issue. Therefore, due to the availability of such devices, the system in this work uses an external RFID reader linked to a mobile computer. The data between the two devices is passed through a Bluetooth channel.

The communication between the SensTag and the RFID reader follows the EPC C1G1 protocol [18]. SensTag provides additional functions over normal, passive EPC C1G1 tags, but the data structure maintains compatibility with the protocol. The data is backscattered from the tag to the reader and is passed on to a serial-to-Bluetooth module via RS232C. The Nokia N800 mobile phone communicates with the Bluetooth module and receives the incoming tags' IDs.

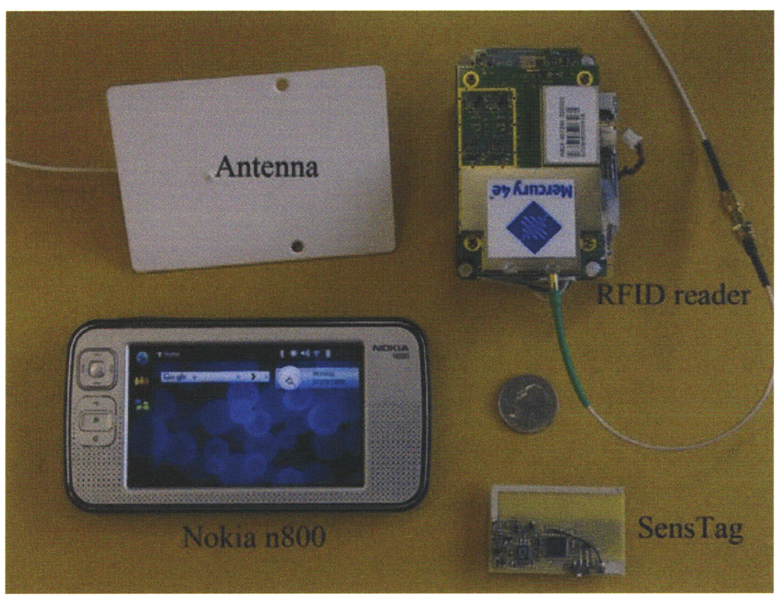


**Figure 2: A photograph of the Infofield system with the antenna, RFID reader, Nokia N800 mobile phone, and SensTag.**

## 3.2 SensTags

SensTag (Sensor enhance RFID Tag) is a UHF RFID tag that communicates with a reader under the EPC C1G1 protocol. To the reader, the SensTag appears to be an ordinary EPC C1G1 tag. SensTag sends the arbitrary sensor data by dynamically changing a dedicated portion of its ID.

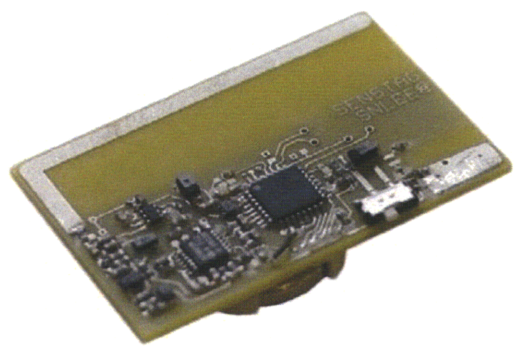

**Figure 3: A Photograph of a SensTag.**

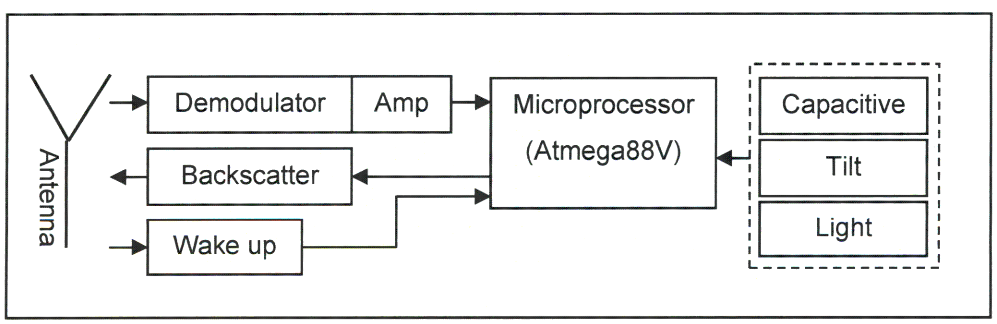


**Figure 4: The Block Diagram of the SensTag circuit.**

SensTag's design is based on prior work on the OpenTag [19]. OpenTag was originally designed for testing privacy features that could not be tested on any commercially available RFID tag, since the chips currently available to create EPC-compliant tags are not programmable, nor do they have sufficient computation power or expandable ports for such purposes. The SensTag is an enhanced version of an OpenTag, with additional sensors and advanced power control.

The system integrates the following components

- A microprocessor Atmega88V
- A whip antenna
- Signal amplifying circuits
- A backscatter circuit
- A wake-up circuit
- Photoresistors
- Capacitive sensors
- Tilt sensors
- A battery (CR2032)

Atmega88V [20] is an 8-bit microprocessor which runs at 4MHz@1.8V~20MHz@3.3V. We chose this micro-processor especially for its low shutdown current (= 0.1uA@1.8V). At 8MHz this processor consumes a peak current of 4mA. The rest of the circuit consumes a rather small portion of the overall current consumed by the tag. Detailed power level will be further discussed in Section 5.1.1. A CR2032 coin cell was selected to meet this specification; the CR2032 supplies a steady 3V voltage and 5mA of current. The capacity of this battery is approximately 220mAH. Peak current consumption of the circuit is about 5.5mA@2.5V and the whole system stably runs at a voltage as low as 2.1V.

The schematic of the SensTag is shown on the next page. Each element will be described in the following subsections.

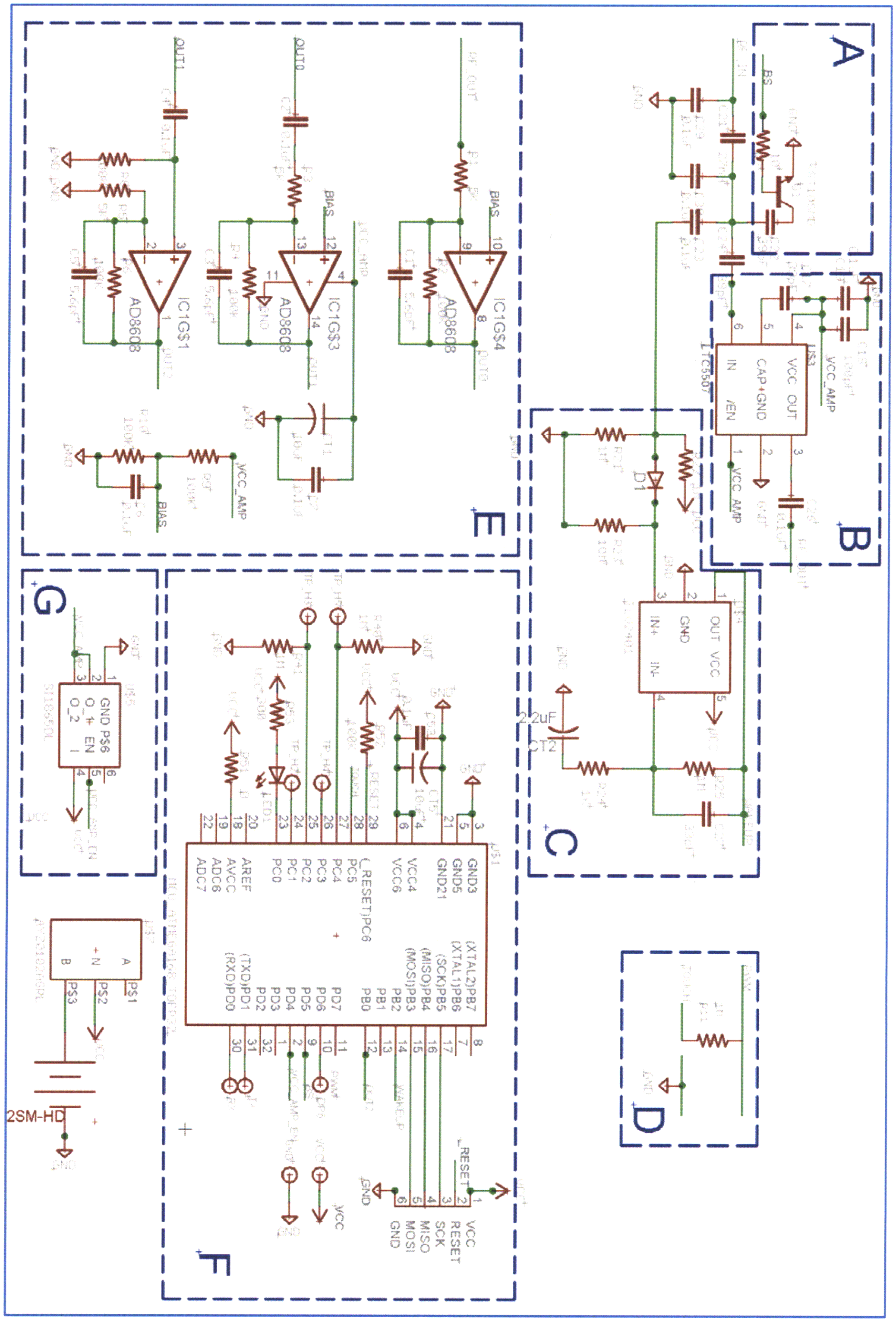


**Figure 5: The schematic of the SensTag; [A] backscatter, [B] power detector /demodulator, [C] wake-up circuit, [D] capacitive sensor, [E] signal amplifier, [F] microprocessor + additional ports for sensor inputs, [G] power switch block.**

### 3.2.1 The EPC protocol

There are a number of ways to design a power-efficient communication protocol between a sensor node and a reader. However, as stated above, SensTag adopts EPC C1G1 protocol to demonstrate how an existing commercial infrastructure could be directly applied to enhance user interactions with tagged objects. This is attractive since it allows us to make use of standard readers and leverage the RFID industry's future investments in reader technology development.

To decode the EPC C1G1 protocol with a general purpose micro-computer (uC), the uC must be able to handle the data bandwidth of the protocol. The C1G1 protocol uses an ASK (amplitude shift key) modulation with the shortest pulse with of 2us. Therefore, in theory, the uC needs to sample a 0.5MHz signal which requires only a 1MHz sampling rate. We used an Atmega88V, which handles most instructions in one cycle; a 2MHz clock speed covers the decoding. Yet, to process the backscatter routine (which is also 2us minimum), the uC had to run above 4MHz. Finally, the system runs at 8MHz for handling sensor measurement and CRC calculation within the time guideline of the EPC protocol.

The latest update on the EPC protocol is the class1 generation2 (C1G2). The C1G2 has some advantages over the C1G1 such as an increased data rate, an enhanced anti-collision mechanism in multi-reader environments, and some additional security features. Despite the performance and the availability of C1G2 over the older C1G1 system, C1G2 requires twice the bandwidth of a C1G1 system, which would demand a higher computation power on the SensTag module. This causes some design issues; a higher voltage supply for activating the microcontroller, a change on the battery type, and an increased complexity on the protocol firmware. Since we did not need the additional features of the C1G2 protocol to demonstrate our scenario, we used the C1G1 on our system.

### 3.2.2 Passive vs. active

A key feature of the RFID tag is the passiveness – being a battery-less tag. A passive RFID tag accumulates power from the signal emitted from the reader and uses it to power up its uC. Then it sends back its ID to the reader using a *backscatter modulation*. In a backscatter modulation, the tag doesn't shoot a signal to the reader; instead it reflects the signal from the reader. The factors that determine the active range in passive RFID systems are (1) the reader's transmit power; (2) reader's antenna efficiency; (3) the tag's antenna efficiency; (4) the power to activate a tag; and (5) the sensitivity of the reader to listen to the backscattered signal from the tag.

In the early stage of this work, we tried to build a power accumulating (= passive) RFID platform which was motivated from the WISP[21]. After we built a prototype of the system, we were able to gain similar power efficiency to a WISP, but it was not enough to satisfy the higher power needs of our system. First, due to size limits, we could not use a full-size fixed antenna for a maximum power transfer from the reader, nor could we afford a huge antenna on a tag for an efficient receiving performance. This reduces the efficiency in transferring power from reader to the tag. In most cases, the range of other wireless communication with a miniature antenna can be increased by the boosting the receiver's gain. But this is not an option for passive RFIDs, and the power that a reader can emit is limited by the Federal Communications Commission (FCC). Second, Infofield was not suitable for a duty cycling power wakeup, which could be used as an option to save power consumption in an asynchronous system. It was not applicable to SensTag because the EPC protocol requires all the tags to be fully active during an anti-collision search. The WISP had tried to evade this problem by accessing only a single tag every few seconds.

The power accumulation of our prototype using cascade voltage doublers is shown below in Figure 6. A 1K load resister was used to model a uC draining 3mA@3V. The uC used in SensTag requires a minimum of 2.2V@8MHz; so, as seen on the graph, the SensTag would work within 4 inches from the reader, which fails to support our scenario.

Therefore, current SensTags require batteries for demonstration, but a very low power consumption using a quasi-passive wakeup circuit [22].

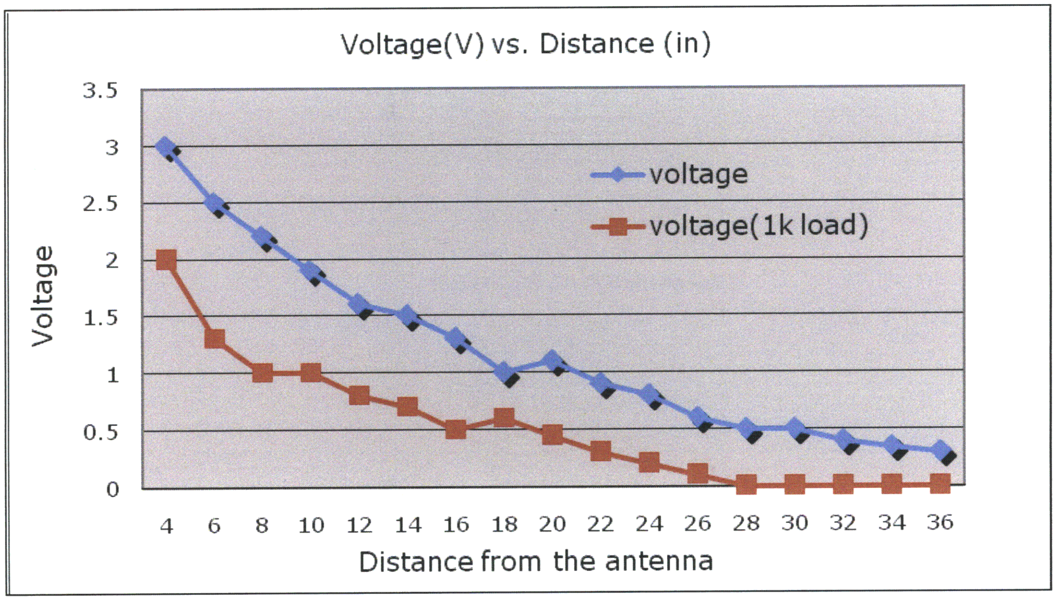


**Figure 6: Voltage gained from the reader vs. distance (SensTag prototype). Blue line represents the harvest voltage with no load. Red line shows the voltage gained when there is a 1K ohm load present.**

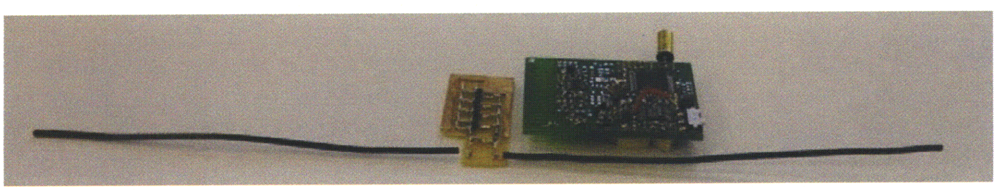

**Figure 7: The photograph of the passive SensTag prototype.**

However, this does not mean that our proposed scheme needs to run on active tags. While our battery powered-platform could enable many other functions, SensTag does not blink an LED, vibrate, or talk back to the user. The features of SensTag are designed to remain passive and can be applied into a passive tag if the tag's IC was designed as an ASIC, a chip-level design [23]. This is due to the gap between the power consumption of a general microcomputer and an application-specific integrated circuit. Generally, a multipurpose uC running on a MHz speed would require 5mW@1.8V, whereas commercially available RFID tags run at sub 1.5V and 100uW.

The rest of Chapter 3 describes the active version of SensTag. The evaluation will be mentioned later in Chapter 5.

### 3.2.3 Antennas for low-power applications

The antenna performance of an RFID tag takes an important role in determining the read range of the RFID system. As for the Infofield, the backward link and the reader's receiver sensitivity determine the read range; a forward link becomes less an issue for the SensTag since it amplifies the incoming signal with the amplifier powered by a battery, resulting in a better receiver sensitivity than a passive tag,

In general, the performance of an antenna is proportional to its dimensions. At lower frequencies, a full-size antenna may be too long, even when wrapped around a few corners. SensTag runs at UHF centered at 916MHz (US regulation), so we chose a quarter-length antenna design for our tag. The radiation pattern of the suggested design is omni-directional, with a gain of -8 to -12 dBi when the board is horizontal. Our final antenna design is shown below.

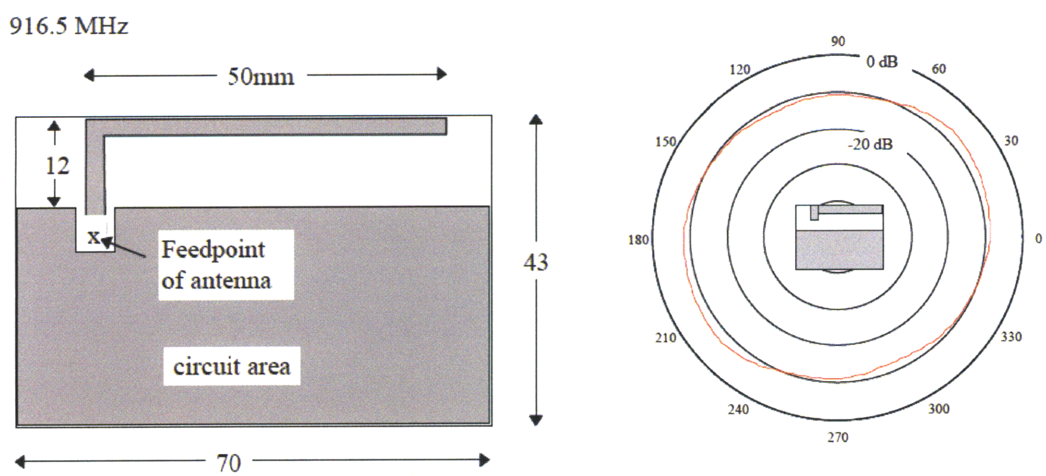


**Figure 8: Characteristics of an open stub antenna [24], Left: antenna's dimension, right: plotting of the antenna's gain.**

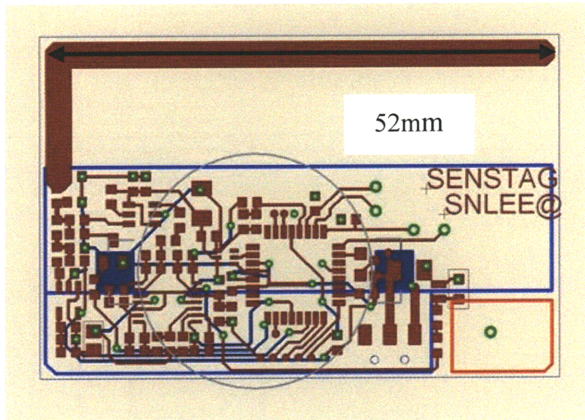


**Figure 9: The antenna layout of the SensTag.**

### 3.2.4 RF front end and backscatter circuit

The RF front end (Figure 5 B,E) of the circuit receives a 902~928MHz carrier signal from the reader. The LTC5507 [25] is a power detector with an input frequency range of 100 kHz ~ 1GHz. The lower boundary of the input range could be limited by adjusting the external capacitor, and this was set to 800MHz in our design. The LTC5507 provides stable input impedance along a wide frequency range and a wide input power range (-34dBm to 14dBm). Also, the LTC5507 can be used as an ASK demodulator for data rates up to 1.5MHz, which covers the data rate of the EPC C1G1 protocol (~500kHz). In our circuit, the LTC5507 serves as an impedance-matching circuit and an ASK demodulator. The modulated signal is then passed on to the op-amp, an AD8608, where the signal is amplified and filtered to match the TTL level. When the Atmega88V is in the power-down mode, both the LTC5507 and the AD8608 are disconnected to extend battery life.

A TLV2401 [26] forms a wake-up circuit (Figure 5 C) that interrupts the uC during its power-down mode. This circuit was inspired from the CargoNet module [22], yet is simplified by leaving out the variable sensitivity control. While a tag is within the active range of an RFID reader, the signal from the RFID reader is significantly stronger than other noise signals at 900MHz, so the system has less concern of a false alarm. A

TLV2401 consumes current less than a 1uA and has a bandwidth of 5.5kHz. The circuit is designed to detect the start frame in the EPC C1G1 protocol.

A bipolar junction transistor forms the backscatter block (Figure 5 A), and the control signal from the uC controls the base of the transistor to open and close a path between the antenna and the GND plane. This toggles the impedance of the antenna, causing a mismatch to change the backscattered amount (reflection) of the signal sent from a reader back to the reader itself. The uC sends back the ID to the reader by modulating a voltage at the base of the transistor.

### 3.2.5 Photo-resistor

The SensTag uses a photo-resistor [27] to monitor the presence of light. The resistance of a photo-resistor varies according to the intensity of light absorbed by the sensor. When a photo-resister is biased by a resistor that forms a voltage divider, the light intensity is measurable by the uC through an ADC port. The PDV-P5001 is sensitive to light that has 400~700nm wavelength, which is the range of wavelength visible to human eye. The PDV-P5001 offers a wide dynamic range at a relatively low cost.

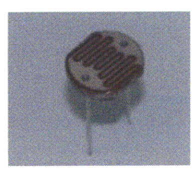

**Figure 10: A photo of the photo-resister embedded in the SensTag (PDV-P5001).**

### 3.2.6 Tilt sensor

The SensTag incorporates a tilt sensor to detect whether a certain direction of the tag is aligned to the gravity force. The sensor is opened or closed according which side of the sensor faces the ground. When the reader asks a tag to send its ID, the tag includes the state of the sensor in its ID and sends the ID to the reader. The reader then decodes the data transmitted from the tag and reads the identity and the state of the tag. The SensTag has a mechanical tilt sensor with a ball floating around a metal container. While it is a simplest structure for a tilt sensor, its size makes it impossible to embed into an RFID chip. Possibly, an alternative low cost structure could be implemented in the future with MEMs technology.

### 3.2.7 Capacitive sensor

A loading mode capacitive sensor was implemented on the SensTag using two I/Os on the Atmega88V. An output pin on the uC drives a transmitter plate with a serial resistor of a magnitude of MΩs, and an ADC input pin monitors the incoming signal from the transmitter plate. The other plate is attached to the GND. When users touch the item, their skin, which is conductive, draws some current to ground, changing the impedance between the two plates. The capacitance change between the two plates affects the slew-rate of the square pulse wave. So by measuring the delay between the drive signal and the incoming signal, the uC can gauge the capacitance between the two plates.

### 3.2.8 SensTag firmware

As described in Section 3.2.1, we have programmed the Atmega88V to emulate the EPC C1G1 protocol. Unlike a commercial passive tag, the SensTag's firmware performs a software radio protocol stack to decode and encode the protocol. This gives a lot of expandability but requires more computation power compared to a state machine that can run only the EPC protocol. The firmware on the Atmega88V was fully programmed with an assembly language [28] for efficient timing controls and to minimize the computational overload. Figure 11 shows the state diagram of the SensTag system. The program sets the hardware system to consume minimal power during the absence of the incoming RF signal. The wakeup circuit explained in Section 3.2.4 interrupts the uC in the power-down mode so that the uC can change to idle mode. Once awake, the uC samples the incoming signal, and when it sees a valid signal, it moves on to the next state.

If the uC does not receive a valid command within the timeout, the uC shuts down the system into its power-down mode.

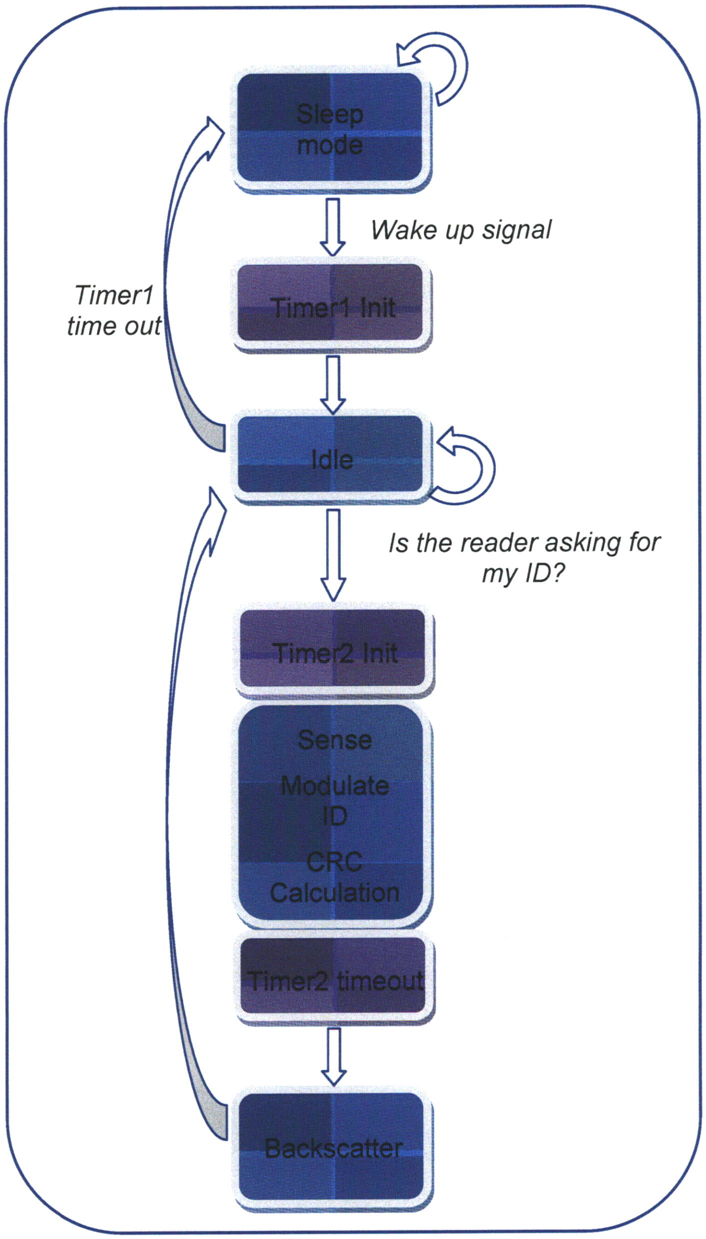


**Figure 11: State diagram of SensTag firmware.**

Upon receiving a valid command from the reader, the SensTag follows the EPC protocol. Currently, the SensTag software supports a subset of EPC C1G1 protocol which – query and anti-collision, but not write commands. When the incoming command asks for the tag's ID, the SensTag reads its sensor values and updates the values in the data field of its ID. A CRC16 calculation on its EPC ID is performed by the uC and the 80bit ID (CRC16 [16bit] + EPC [64bit]) is added to the queue. This is backscattered to the reader when an amount of time has passed from the point the command had been received by the SensTag.

### 3.3 RFID reader

There was not much choice in finding a suitable – both in size and power consumption – mobile UHF RFID reader in the market. Most compact RFID readers, which are approximately the size of a card deck, were not actually designed for mobile applications, but instead for compact installations in buildings. These readers were targeted to work with a huge antenna and still required a large power supply. The final two candidates supporting both the EPC C1G1 and the C1G2 protocols were Skyetek M9 [29] and Mercury 4e [30]. These two modules support data I/O over RS-232C, which was another requirement to fit into our system.

The M9 from Skyetek is small and accessible, supporting a full control using the command sets. An attractive characteristic of this module is the support for various speeds of the C1G1 protocol. The module does not limit itself to a 16us data pulse width, but instead it sends a 48us pulse that is a 3 times stretched version of an official C1G1 protocol. The passive RFID tags we owned were compatible to the slower versions of the C1G1 protocol. This worked as an advantage to our system. The SensTag could operate at a much slower speed (1MHz) than the original design (4MHz). However, the M9 module was optimized on passive tags, which normally have a forward link limitation rather than a backward link; the module had set a sensitivity limit on its receiver. Active tags gain a longer forward link range over a passive tag, but there isn't an improvement on backward-link performance, since reflection is dependent on the dimension of the antenna. Therefore, we switched to a Mercury 4e module as we could not achieve the appropriate read range from the M9 module.

The Mercury 4e from ThingMagic is bigger than the M9, but has better receiver sensitivity and stronger transmit power. We found a significant range increase compared to the previous module. In a controlled environment, the reader could read SensTags up to 1.8 meters.

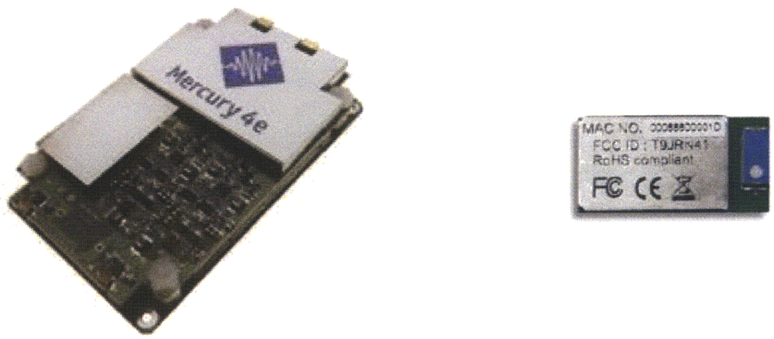


**Figure 12: Left: A Mercury 4e module (ThingMagic). Right: A Bluetooth module (Roving networks).**

One of the constraints of the UHF RFID reader module is the power consumption; the system needs to send a high-energy field to a distance, which makes the system fundamentally power consuming. The Mercury 4e draws a peak of 1.2A@5.5V and 0.6A@5.5V in average. So we attached a 6V 2.5AH battery pack of 4 AA batteries connected in serial. The RS-232 port on the Mercury 4e is connected to a Bluetooth module (RN-41 Roving network). The Bluetooth module sends the serial data over Bluetooth channel and vice versa.

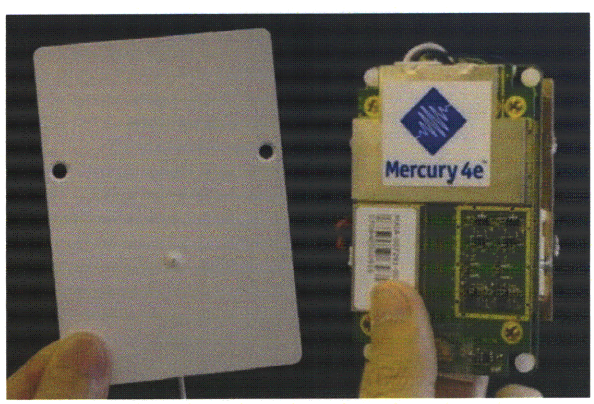


**Figure 13: Left: The 6dBi omni-directional antenna (10*7 cm) connected to the Mercury 4e RFID reader. Right: The RFID module consists of a Mercury 4e reader, a battery pack, and a Bluetooth module.**

A Nokia N800 was used as a mobile display to visualize the Infofield system. Running on a Linux, this 800*480 screen mobile computer supports 802.11b, Bluetooth, and an easy programming environment with Python libraries. The database and the codes were handled by the N800. The information on the screen can also be accessed using the touch screen or the scroll buttons on the left. The Nokia N800 also has an external speaker which we used to output music or alarms during the user demonstration.


**Figure 14: A photo of a Nokia mobile phone N800 used in the experiment.**

# Chapter 4

# User Interface

## 4.1 Overview

In the framework of the Infofield, we have attempted to minimize transactions between the users and the mobile phone while users are accessing an item's information out of a pool of objects. In lieu of a point-shoot-retrieve sequence of traditional 1:1 interaction, the mobile display shows the list of the objects near the user and the specific object that the system presumes as the object of the user's best interest. Far-field RFID enables ambient detection of multiple tags in the surroundings, but, in return, faces a singulation issue.

We introduce three levels of interest – how much an item is interacting with the user. The first level is 'within bound.' An item within the distance that the RFID reader can read (approximately 1.5 meter range) is considered as level one. The second level is based on touch; touching or holding an object generally indicates that the user is more aware of the object than just standing near it. The capacitive sensor integrated onto the surface of an item measures the variation of the impedance to detect whether the user is touching its hosted item. Measuring touch could be a good method to detect the beginning and end of an interaction. However, the system may not be able to detect the item of interest if a user holds a pile of books while skimming through the book at the top of the pile. In this situation, knowing the status of the books (e.g., the book is opened) will help the system to point out which is the item of interest. An item reaches the third level when the user interacts with it by changing the status of the item.

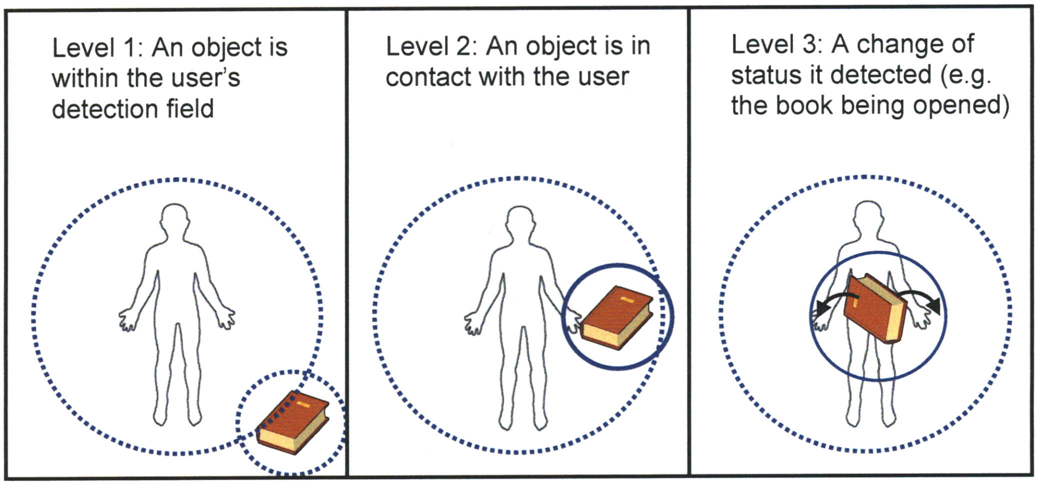


**Figure 15: The three levels of interaction.**

## 4.2 Tagging locations

Generally, an RFID location-tracking system uses a grid of RFID readers that contain their location information to track RFID tagged objects. In this infrastructure, the trail of an item can be drawn from a connection of the locations where the item has been spotted by the RFID readers. This is useful when the size of the space is limited and the system needs to track numerous moving objects. For example, security access card readers in buildings log the members' trails, when and where they were in the building. Having a new member in the building takes a minor increase in cost, which is just an extra access card. On the other side, these systems do not offer cost-effective scalability when we want to expand the building, reconfigure the access points, or deploy a large-scale outdoor system.

In contrast to previous RFID systems, the Infofield takes exactly the opposite approach. Instead of placing a limited number of RFID readers at the wanted locations, we deploy passive RFID tags into permanent structures such as doors, floors, cabinets, and desks. These tags contain location information or a pointer to a location database in the server to act as location beacons. Tags are much cheaper, smaller, and do not require power as opposed to an RFID reader, so expanding the location grid is as simple as sticking a few more RFID tags in the building. This approach maximizes its advantage when there is a small user group in a large space.

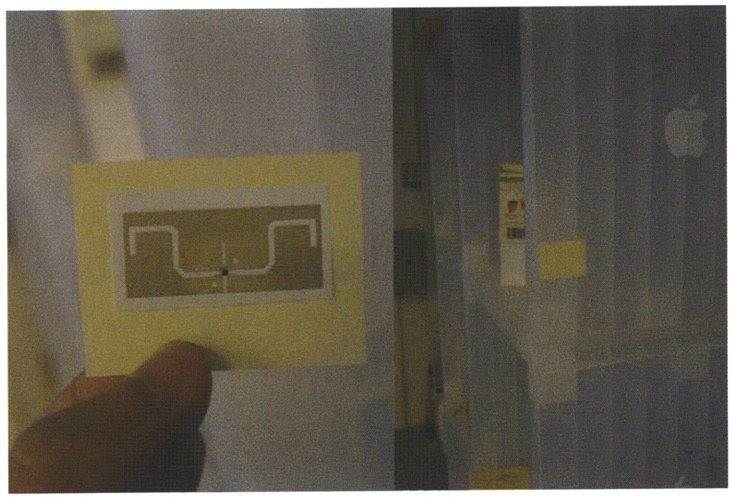

**Figure 16: Photo of a passive EPC tag for location tagging.**

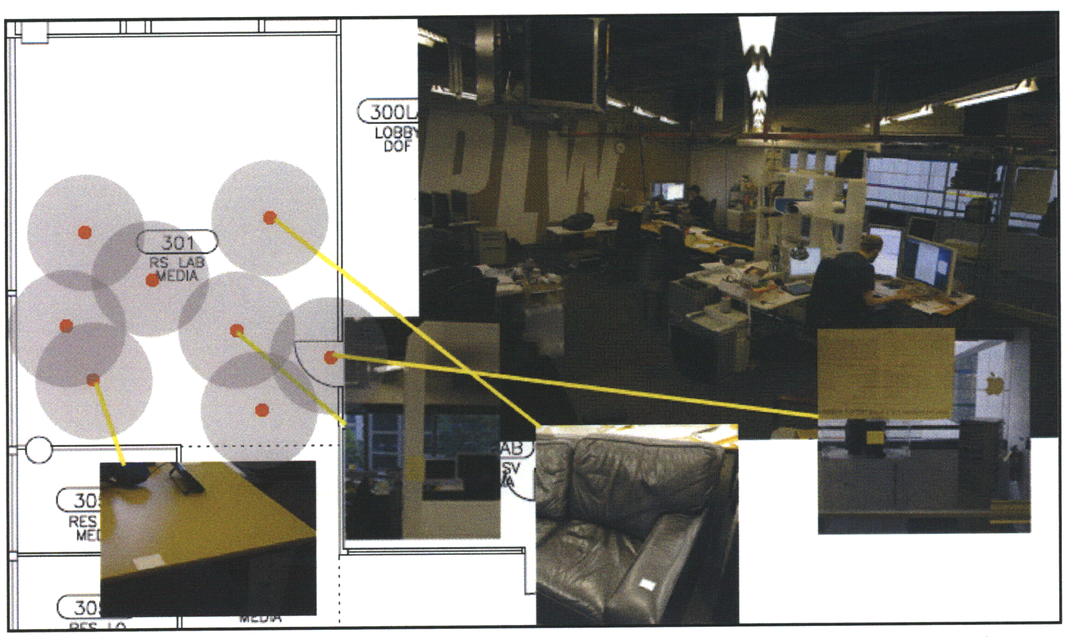


**Figure 17: Location tags were placed on non-moving objects such as desks, doors, sofa, and other furniture in the room.**

As shown in Figure 16, an EPC C1G2 RFID tag is attached to a Post-It for tagging convenience. We then programmed each tag with a unique ID mapped to the location information. These tags were tagged onto various pieces of furniture and building parts in the office as illustrated in Figure 17. The type of RFID tag in Figure 16 typically covers a 1-meter radius circle. After the simple installation, location information with the matching ID was added into the database. In the future, furniture with EPC tags could be used as location beacons without any modification.

## 4.3 Tagging physical objects

SensTags monitor the status of their hosted items, such as whether they have been picked up or how they are being used. For example, what would best describe the use of a book is whether it is held and what page the user has opened. The SensTag senses whether the user is holding a book and what page is opened at that moment and sends the static ID and sensor values back to the RFID reader. The values that describe the hosted item vary according to what the host item is, so modeling the usage of all the unique items we see would be an interesting challenge. In the following subsections, we will demonstrate some general concepts of embedding a sensor tag on a couple of objects that we see in a everyday environment.

### 4.3.1 A poster

A bulletin board full of posters – how could we select one out of many? Figure 18 shows a poster with a simple capacitive sensor (two pieces of metal tape) connected to a SensTag. The SensTag, embedded under the paper, reads the change of the capacitance between the two terminals and modulates the sensor data field in addition to its static ID. The static ID refers to the URL that links to the Website that provides more information about the topic on the poster. When the system receives the ID with a data field indicating the capacitive sensor has been interrupted, the mobile phone immediately pops up the Webpage pointed to by the static ID. In this scenario, the users can select the information that they want to access by manipulating the physical objects instead of selecting it from the screen.

An alternative way of detecting a touch is to use a photo-resistor. When a finger covers the photo-resistor, the SensTag would sense change of voltage and refer it as an event. This is useful when the environment is highly conductive, or in case the users try to trigger the sensor with their gloves on. On the other hand, a photo-resistor may give a false alarm in a change of lighting (e.g, turning of the light in the area). This could be avoided by using two or more photo-resistors in different areas to catch an exclusive value of the two sensors. However, the disadvantage of photo sensing is that it does not cover a large detection area because the photo sensing requires a complete termination of lights into the sensor for a discrete change, so the sensing area has to be smaller than a finger tip. A grid of light sensors may overcome the lack of sensing area, but increases the complexity and the cost of the system.

While a capacitive sensor may give a false alarm in conductive conditions (e.g, humid or metal environment), it covers a good range of sensing areas with a single input. It also has an advantage in cost because the sensor can be drawn on surface of the tag with conductive inks. Therefore, with a combination of the two, we could increase the resistivity of the system to the changing environment.

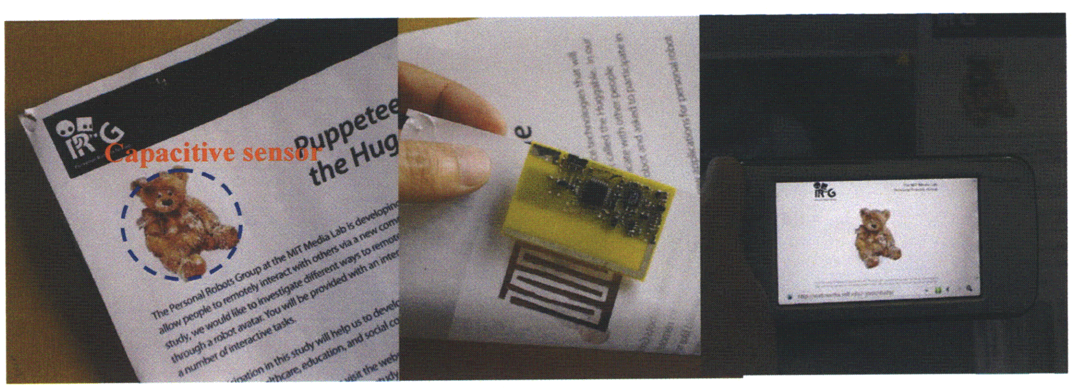


**Figure 18: A capacitive sensor for a poster.**

### 4.3.2 A book

Take a look around your room. You may find a good number of books. Every book has a different length and size, but shares the same interface, thus making it easy to model the interaction between users and books. ReachMedia [13] used an RFID-reader-integrated wristband to identify the book that a user holds and tried to search and retrieve additional information from the book by monitoring the user's gestures. Galatia [15] has also demonstrated its concepts with books. An RF module on the book blinks its LED when its contents match the user's preferences as a physical feedback of a keyword match.

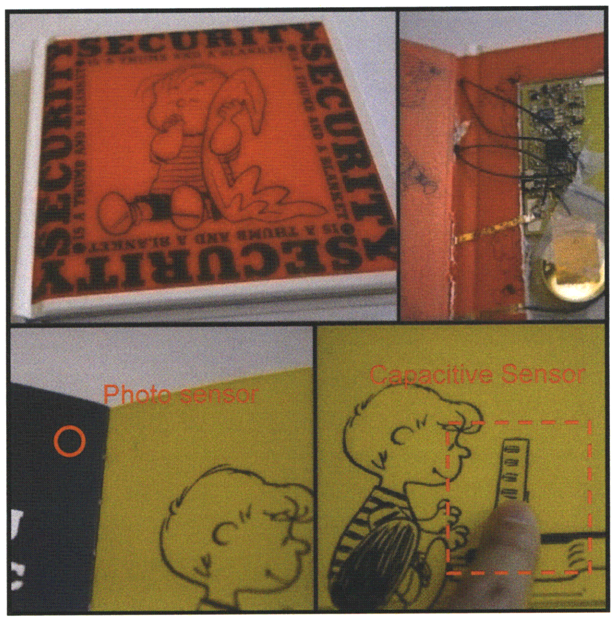


**Figure 19: Embedding a SensTag into a book.**

Figure 19 shows how a SensTag is built into a book. Each page has a photo-resistor under a small hole. When the page is opened, the light passes through the hole onto the photo-resistor causing a change on its resistance. We neglect the case when the book is opened in total darkness, assuming that users do not attempt to access a certain page while they are not able to see it. The SensTag modulates its ID to indicate what pages have been opened. The Infofield receives the ID and displays the contents related to the page (e.g., video clips, music, and Webpages). The multimedia contents could be retrieved by manipulating the N800 touch screen, but also by manipulating the book itself. For instance, the bottom right photo of Figure 19 shows how the user could listen to the music linked to the piano. A capacitive sensor is embedded under the piano and when the user touches it, the N800 starts playing the music. When the user closes the book, the system supposes that the user is no longer interested and stops the music.

### 4.3.3 A teddy bear

A teddy bear with an integrated SensTag is shown in Figure 20. Two strips of wires drawn from the SensTag form a capacitive sensing unit. These wires are woven into one arm of the bear. The ID of the embedded SensTag is modulated when the user squeezes the arm of the bear. With conductive threads woven into fabrics, this concept could be generally applied to fabric-based objects.

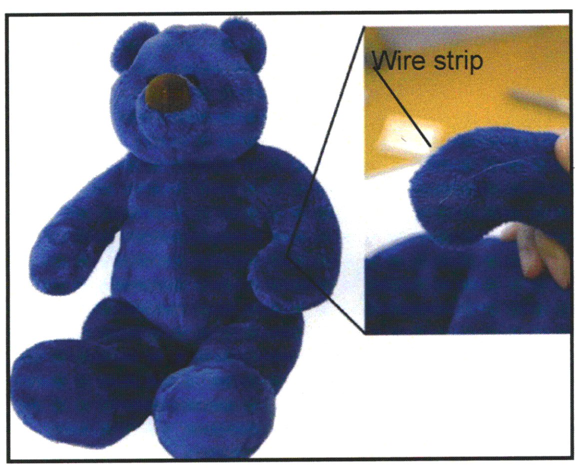


**Figure 20: A SensTag in a teddy bear.**

### 4.3.4 A box

A SensTag is augmented into a box. The photo-resistor catches the light intensity in the box which indicates whether the box is opened, the tilt sensor detects whether the box is upright, and the wire strips around the edge of the box sense the change of capacitance to detect whether a user is holding the box. These concepts can be widely applied to objects like boxes, containers, and bottles that have a preferred orientation, or that would spoil when opened. In the supply chain, this concept is also very useful since most of the items are boxes; the tilt sensor of an RFID tag could warn the supplier when a box flips over.

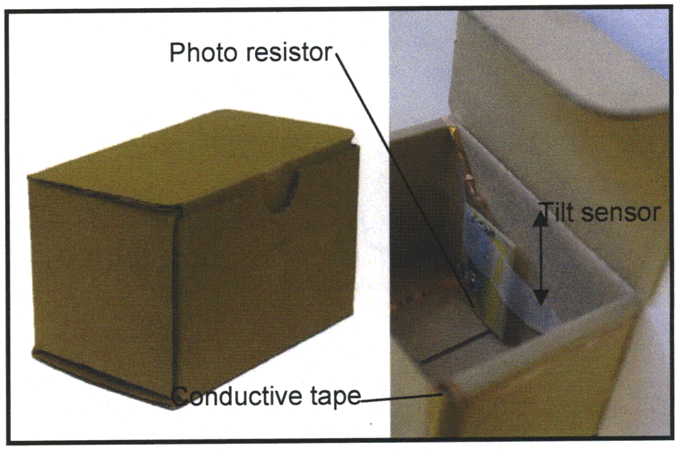


**Figure 21: A box with a SensTag.**

## 4.5 Wearing the reader

The Infofield system was worn in three separate pieces; the antenna, the reader, and the mobile device. The antenna is positioned at the center of the body to center the sphere-field that embraces the user. Alternatively, the antenna could be clipped onto the belt or hung using a neck strap. However, during the test, we found that the field generated by the antenna was not omni-directional due to the body effect. This is further discussed in Section 5.2. The position of the reader shows no influence on the performance, but it is kept inside the user's pocket due to the weight.

The N800 mobile phone is used in the way that a mobile device of similar size would typically be used. While it is stored in one's pocket, it gives the user acoustic feedback when the preferred information has been found nearby. The position of the N800 is also irrelevant to the tag-reading performance, which is comparable to other scenarios where the mobile phone has to face or contact the barcodes or RFID tags to access information.

The targeted form factor of our Infofield system is a size that can be integrated into a mobile phone such as the NFC-enabled phone from Nokia. This system would be invisible and less obtrusive to the user. Ideally, the N800 mobile phone would serve as a RFID-reader-integrated phone

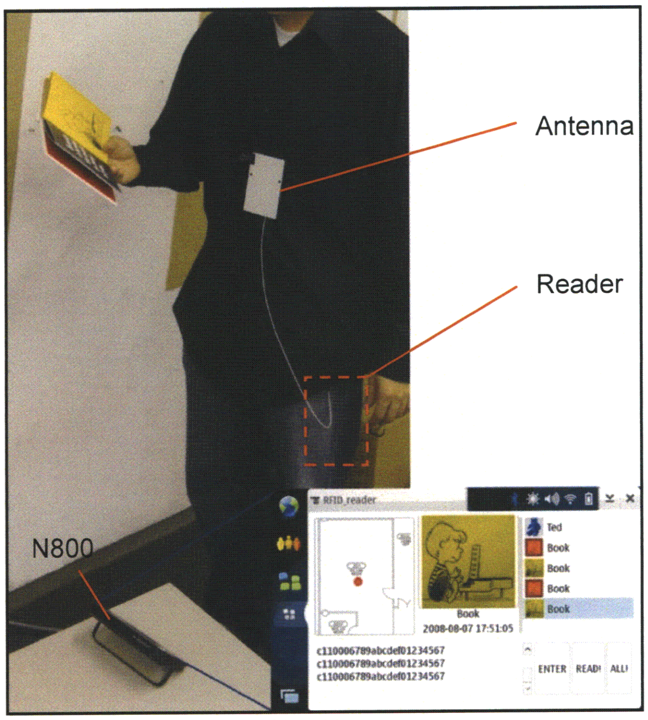


**Figure 22: A photo of the Infofield system worn by a user; the UI on N800 screen (bottom right).**

## 4.6 Displaying the data

Figure 23 illustrates the graphic user interface of the Infofield system. The screen shows (a) location of a current/selected item; (b) the picture of the item; (c) time when the item was detected; (d) list of items; (e) control buttons; and (f) raw EPC ID. These values are updated in real time as the mobile phone receives a list of incoming IDs from the Mercury 4e reader. The buttons in (e) control the RFID reader to start, stop, and select which types of RFID tag it should scan. The SensTag is compatible to EPC C1G1 protocol and most of the passive tags we have used were based on EPC C1G2. By selecting 'All' the Mercury reader scans all the C1G1 tags and then C1G2 tags through an interval of 400 milliseconds each. If 'Gen1' is selected instead of 'all' the SensTag will only read C1G1 tags, which doubles the read rate of C1G1 tags for a better sample rate. This is repeated until a 'Stop' command is received.

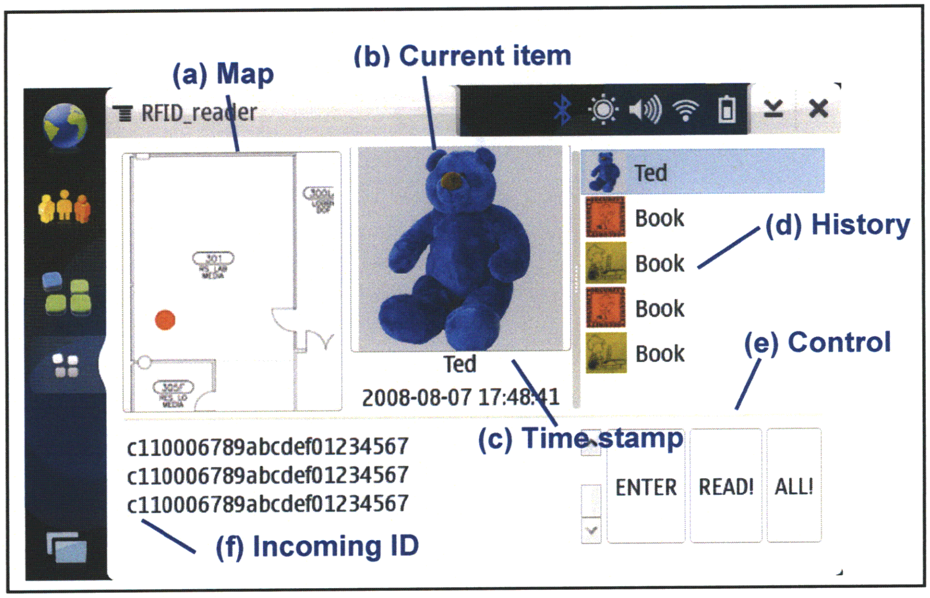


**Figure 23: The basic visualization of the Infofield system.**

Once a valid ID is received, the N800 system reads the parameters of the matching ID from the database. There are two sets of databases in the Infofield system. One is the database of location tags, and the other stores the rest of the tags. The item information of a location tag is not shown on the display; the system only estimates the location from the incoming location tag ID and plots it on the map. When the system sees an ID that is registered in the second database, it displays the photo (b) of the specific item. The photo illustrates the status of the item. The time (c) and location are tagged onto the event and kept in the history panel (d). When the user scrolls back and clicks an item in the history panel, (a) (b) (c) shows the record of the selected item.

The interface described in 4.6 enables the following features:

- Preference match

- Indoor location
- Find item – tagging the last seen location with items
- logging of daily activities
- Access to information through physical interaction

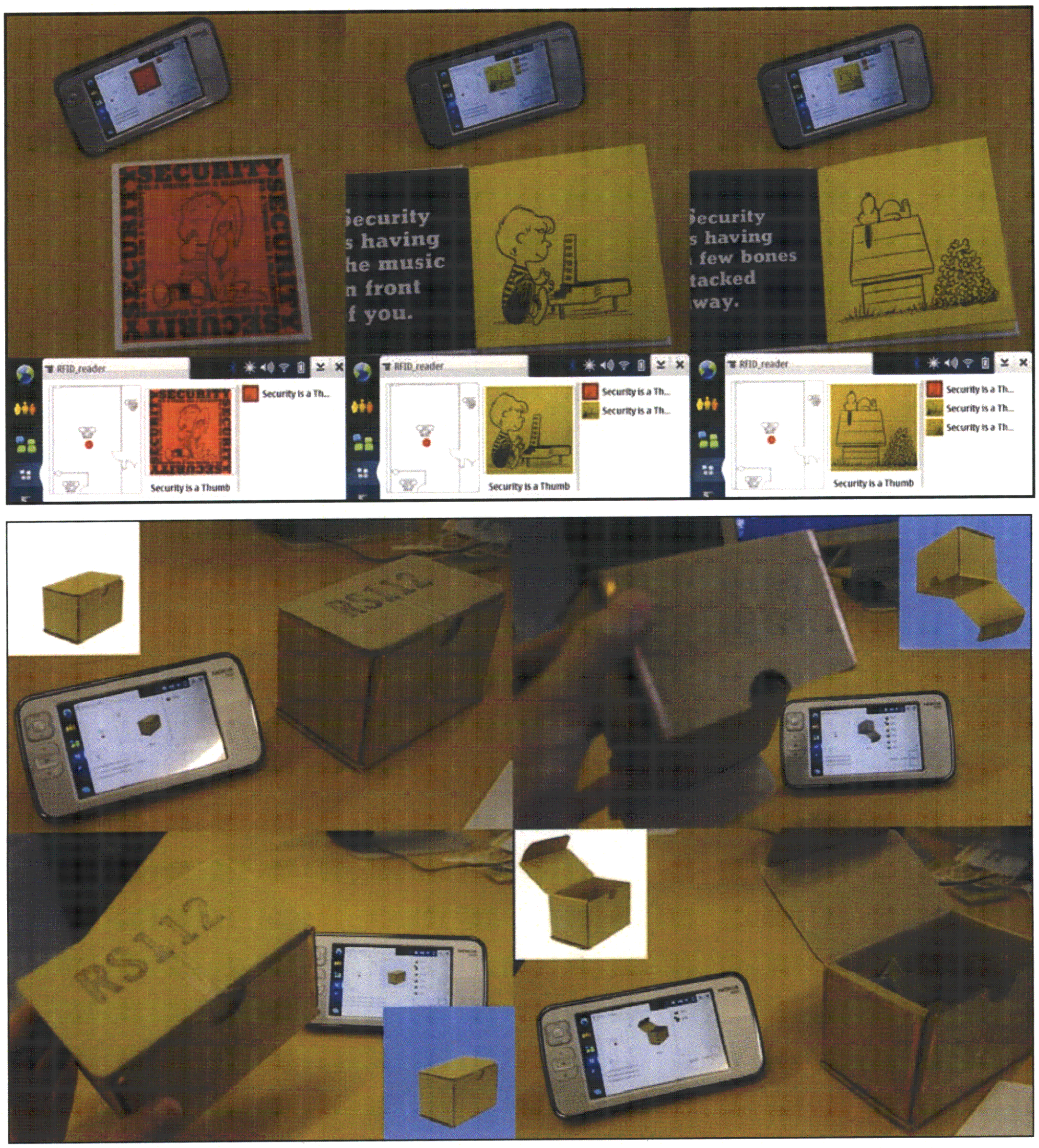


**Figure 24: The interactive book, the mobile reader recognizes the opened pages (top). The interactive box, the reader detects whether the box is opened, touched, or flipped upside down (bottom).**

# Chapter 5

# Evaluations

## 5.1 System performance

### 5.1.1 Power consumption of the system

As we described in Section 3.2.2, the SensTag is designed to be a platform supporting a full programmability and the compatibility with the EPC C1G1 protocol, yet it restricts its functions to a level that can possibly be adopted by a passive RFID system. Due to the limit of a general microcomputer, the power consumption exceeds the level that a miniature antenna could harvest from an RFID reader. So we use a battery to power up our device, but the overall current consumption – although not as low as that of a passive tag – has been minimized.

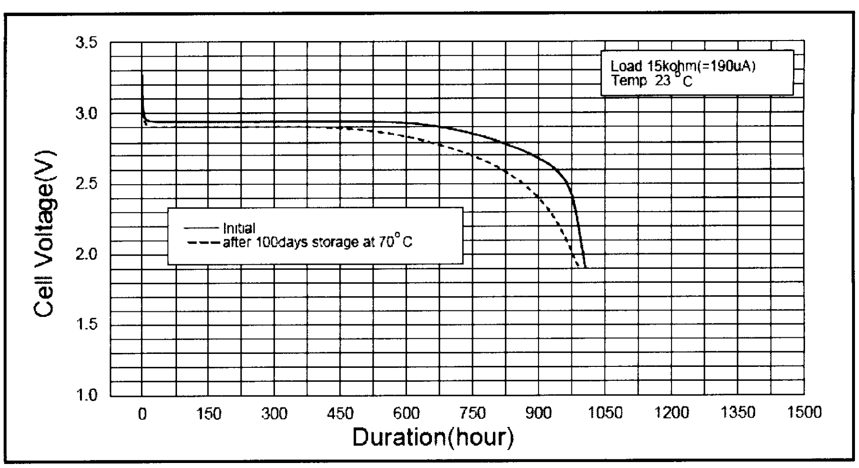


**Figure 25: Discharge Characteristic of a CR2032 battery.**

The CR2032 battery [31] is a lithium coin battery with a 200mAH capacity. Figure 25 shows a nominal voltage of 2.9V at sub 100uA discharge in the lab measurement. The voltage of this battery drops down to 2.5V at a 5mA discharge rate. The cell maintains a steady voltage until 70% of the full capacity has been discharged. We measured the power consumption of the SensTag at 2.5V when active and 2.9V when in power-down mode.

The Atmega88V datasheet [20] states that the current consumption for a power-down mode is 0.1uA@1.8V. In 2.2V~3.0V range, the current measurement was kept under 1uA. When in power-down mode, the TLV2401 consumes 1uA and the bias circuit consumes 1.5uA. The powers for other circuits are disconnected during the power-down mode, so the overall current consumption should be 3.5uA. However, due to some parasitic currents, the total current measures 10uA@3V. For now, when the SensTag is in power-down mode, a CR2032 can maintain a SensTag for 20000 hours (= 200mAH/10uA), which is equivalent to 833 days or over 2 years.

| | ACTIVE [uA @2.5V] | POWER DOWN [uA @ 3.0V] |
|---|---|---|
| Atmega88V | 2500 | 0.6 |
| TLV2401 | 2.5 | 2.5 |
| LTC 5507+AD8608 | 2000 | 0 |
| Tilt sensor | < 1 | 0 |
| Capacitive sensor | < 1 | 0 |
| Light sensor | < 1 | 0 |
| unknown | - | 7 |
| Total | 5000 (peak) | 10 |

**Figure 26: power consumption of SensTag.**

At 8MHz, the SensTag consumes a peak current of 5mA@2.5V with an average of 3mA@2.5V. This is equivalent of 60 hours of continuous use. Depending on how much the RFID reader interrupts a SensTag, the battery life spans from 2.5 days to 2 years. Considering a 30 minute use a day, the lifetime of a SensTag battery will be approximately 4 months. The lifetime of the battery is sufficient to last during the demonstrations, reducing the unwieldiness of replacing batteries.

As for the RFID reader, the Mercury 4e consumes a peak of 1.2A@5.5V whereas a battery pack of 4AA batteries is 2700mAH@6V. The Bluetooth module draws 30mA of current, barely a fraction of what Mercury 4e consumes. So, the battery lasts for 2~3 hours. Duty cycling the RFID reader extends the battery life, but in turn lowers the read cycle.

### 5.1.2 Effective read range of the Infofield system

Being an active tag, the SensTag amplifies the incoming signal with active components and hence shows better receiver sensitivity than a passive tag. Here is a short calculation on what we could expect from the system.

For this signal to be received by the SensTag the following condition has to be satisfied.

$$S_r >= P_t + G_{tot} - L \qquad (5.1)$$

Where

$S_r$ = Sensitivity of the receiver (SensTag)

$P_t$ = Power transmitted by the transmitter (Mercury 4e)

$G_{tot}$ = Gain of the antenna + loss from cables

L = Path loss

The maximum sensitivity of the SensTag is -20dBm, which is derived from the sensitivity of the LTC5507 IC (-32dBm) and the open stub antenna (-10dBm – assuming it has been ideally matched). The signal is transmitted from the Mercury 4e with a power of 27dBm, through the antenna which specifies a 6dBi gain and a cable with a typical 0.5dBm loss.

If we use a Free Space model the path loss

$$L = 32.45 + 20Log_{10}(distance[km]) + 20Log_{10}(frequency[Mhz]) \qquad (5.2)$$

Then

$$20\text{Log}_{10}(\text{distance[km]}) = 27+5.5-(-20) -32.45 -20\text{Log}_{10}(916) =-39.19 \quad (5.3)$$

$$\text{Distance[km]} = 10\text{^}(-39.19/20) = 0.011 = 11\text{m} \quad (5.4)$$

So the estimated maximum distance is 11m in a very ideal open space. Our result was 4 meters (maximum) and considering that this was tested indoors, the result was reasonable.

Figure 27 illustrates the real range of how far a SensTag can listen to the reader (the forward link [area in blue]), and the range that the reader can receive the backscattered signal (the backward link [area in pink]). The forward link can be measured with the status LED on SensTag; the LED blinks whenever the tag backscatters its ID.

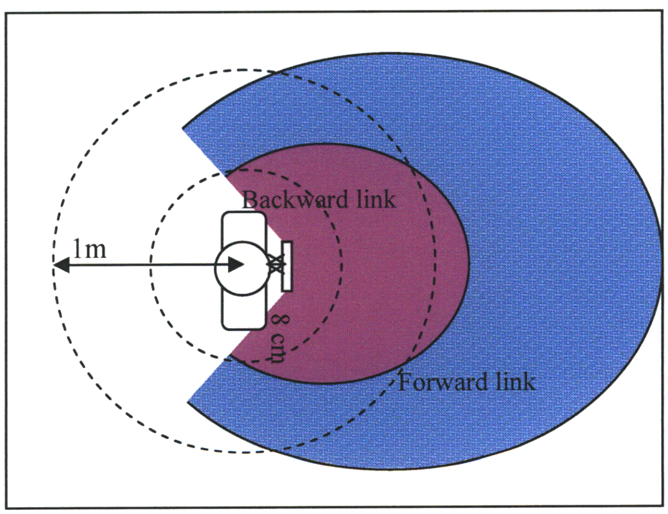


**Figure 27: Illustration of the forward (blue area) and backward (red area) link of RF communication. The illustrated area show a mean value: the actual measurements fluctuate and do not show a smooth rounded shape.**

Generally, passive tags have a shorter forward link than backward link, so the prior factor limits its effective communication distance. On the other hand, the SensTag has a longer forward link using an amplifying circuit. So the backward link limits the effective communication range between the reader and the tag. The backward link is determined by the reader's carrier signal strength (a), the amount of reflection the tag can make (b), and the receiver sensitivity of the reader (c). In fact, the transmit power (a) is a factor that is restricted by law and (b) is relevant to the dimension of the antenna, but we were surprised to find that (c) was also limited by the reader. We assumed that the reader's receiver sensitivity had been adjusted to be comparable to the forward link of a passive tag, as an excessive sensitivity would only increase the signal-to-noise ratio. Therefore, we could not fully achieve a read range that may be expected from an active RFID system.

Due to the body effect, the signal emitted from the antenna was absorbed and distorted by the body and the arms. Also, nulls created from reflection and multi-path interference decreased the system's performance. So the Infofield created around the user is not a perfect sphere and does not center at the antenna. On average, the tags worked inside the range illustrated in Figure 27, but did not ensure a robust read performance as the tags got further from the reader.

### 5.1.3 Data bandwidth

The sampling rates of the sensors are limited less by the sensor's response time or the microprocessor's performance; rather, they are dependent on how often the RFID reader queries the tags. The SensTag does not store the sampled data in its memory, but sends the current data to the reader when it is asked to do so. If we make an assumption that the RF channel guarantees a zero percent read failure, a cycle of sending a command and reading back a tag's ID can take as short as 2ms. Theoretically that would be 500 reads per second. However, this channel needs to be shared by multiple tags in the field so the read rate for each tag is divided down to 500/N (N = number of tags in the given field). Plus, the EPC protocol uses anti-collision methods to access multiple tags. The reader sends out a SCROLLID command asking all the tags to answer, and when it detects a collision, it does a binary tree sort. The reader first asks all tags that start with a '1' to answer and if collision is detected again, it asks for tags that start with an '11' to answer. The commands that were used to sort out the tags do not contribute to the read rate, and this decreases the actual reading rate, especially when there are a lot of tags in the field.

By removing the assumption that the RF field is fail free, the actual read rate drops even more.

Moreover, the communication channel between the reader and the N800 plus the visualization processes had caused extra delays between the sampling timeframes. First, the reader we used, Mercury 4e, did not permit an access to the raw data simultaneously. Instead we asked the reader to scan for a specific length of time and then let the reader return a list of IDs found in the field within the timeframe. If the timeframe is set to be short, we could get more samples per second for better motion detecting. But if the timeframe is too short, the system may not access all the tags within the timeframe. With trial and error, we found that the timeframe of 200ms was optimal for a tag population of one to ten. After a 200ms timeframe, the N800 asks the reader to send the list of IDs. While the Mercury 4e sends the data through the serial port, the next scan timeframe cannot be processed concurrently and this increases the delay between the timeframes. Second, there were some delays in displaying the icons. Python codes were slightly slow, but through optimizations this can be minimized. Overall, the Infofield system performs a 500ms update for SensTags (EPC C1G1) and a 1000ms update for both EPC C1G1 and C1G2 tags; the latter is doubled because SensTags(C1G1) and passive tags (C1G2) tags need to be scanned in different timeframes.

Therefore, to examine only the SensTag's capability, we also used a Mercury 4 (not the 4E) fixed reader with an optimum antenna to text our tags. The Mercury 4 has a better power coverage and sensitivity over the compact version Mercury 4e, so was able to sample 30~70samples per second. The result is provided in Appendix B.

## 5.2 User evaluation

We have performed a preliminary study to verify how accurate the system reads the current activity of the users. The data received from the SensTags are used to analyze whether the hosted item is nearby, the user is touching the item, or the status of the item has changed. The information from the objects is fed into the rating system, and the N800 displays the most probable object that the user is engaged in at the moment.

### 5.2.1 The experiment

We conducted the following tests with five volunteers in our research group, all of whom had little background on how the Infofield system worked. Each was asked to wear the system and interact with three objects on the desk; a box, a book, and a bottle. Before the experiment, we explained how the three objects could be opened or oriented, and asked the users to use the item in the order that is listed on the instructions found in Section 5.2.1. We reminded the users to handle the items as they would if actually using them.

**Test A**

Each item was placed around the room, within the user's vicinity. The user was asked to bring the items to the desk. The users were asked to observe the N800 display while approaching the items. Through this test, the user could experience how far the mobile reader could detect the RFID-tagged object.

**Test B**

In this test, we test how accurately the system recognizes the activity of the user. Instructions were given to the user and the user was asked to follow the 13 tasks in the listed order. No feedback was given to the user during the test. We observed the user's actions and checked if the description on the N800 screen matched the activity of the user. This test is repeated twice.

**Instructions**

1. Pick up the bottle
2. Leave the bottle on the desk
3. Pick up the book
4. Open page1
5. Open page2
6. Close the book
7. Leave the book on the desk
8. Pick up the box

9. Open the box
10. Close the box
11. Flip the box upside down
12. Flip the box right up
13. Leave the box down on the desk

**Test C**

Now we let the users have the access to the N800 display so that they could get instant feedback on what they are doing. We asked the users to wait for the system to give feedback that indicates what they are doing before moving onto the next procedures. This test was also conducted twice per user.

### 5.2.2 Analysis

The results of the tests are as below. The accuracy is the number of correct guesses that the system made over the total number of tasks that the user did.

| User | Test B(1) | Test B(2) | Test C(1,2) |
|---|---|---|---|
| 1 | 12/13 | 12/13 | 26/26 |
| 2 | 8/13 | 7/13 | 25/26 |
| 3 | 11/13 | 12/13 | 26/26 |
| 4 | 10/13 | 10/13 | 24/26 |
| 5 | 12/13 | 13/13 | 26/26 |
| Total | 53/65 | 54/65 | 127/130 |
| **Accuracy** | **82.3%** | | **97.7%** |

**Figure 28: Results from tests B and C.**

The purpose of Test B was to measure the users' activities when they have no feedback from the system. This would be a situation where the users keep the mobile phones in their pockets and the mobile phones perform ambient detection of the surroundings. Applications that aim to provide awareness to the user (e.g., preference match or alert system) will be based on this type of data. As a result, the Infofield performed with 82.3% accuracy.

On the other hand, Test C measured how well the system could detect the users' activities when they get feedback from the display. This would be a situation where the users monitor their mobile phones and explicitly manipulate the items in order to access the information linked to them. The accuracy of Test C (97.7%) was better than the previous result of Test B.

We assumed that the accuracy improvement of Test C was not affected by the sequence of the test procedures. During Test B, the users did not have any feedback on how they should manipulate the items to get better results. The unvarying results between Test B(1) and Test B(2) support our assumption, because if the improvement on Test C was due to the experience from Test B, Test B(2) should have a better result than Test B(1). The main reason that Test B resulted a lower accuracy was the unstable sampling of the Infofield.

Figure 29 is example of the data, which was extracted from the result of one participant who showed a 100% match in Test C. The signals indicate the values extracted from the sensor data field in the incoming IDs. The icons below the graph are what was actually displayed to the user by the system at each moment. We could observe the undersampling in the 80~120 second period. As discussed in Section 5.1.3, this is due to the limitation of the mobile reader system; we could get a higher sampling rate with a Mercury 4 reader [Appendix B]. Upon further optimization, the Infofield will be capable of detecting more active status changes with better accuracy.

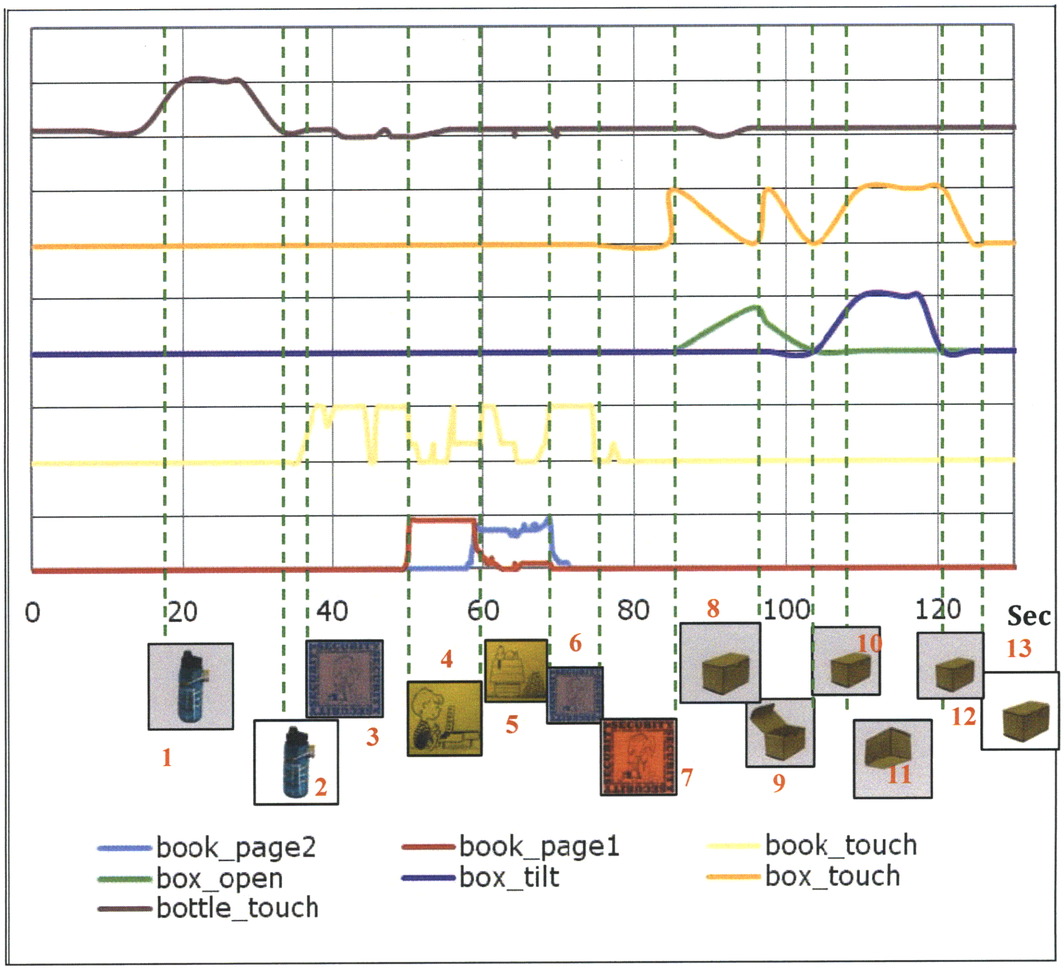


**Figure 29: The raw data / photos that were displayed by the Infofield system based on its prediction.**

### 5.2.3 Comments

The participants answered the questionnaires [Appendix C] after the quantitative tests. Generally, the participants agreed that the unobtrusive logging of physical activities will enable the support of human memory and recommendation systems. But most were less concerned about the privacy issues as long as the data was kept in their phones.

However, the participants had different opinions on how much data to which they want to be exposed. For scenarios where the system tells the user if a preferred item is nearby, half of the users answered that they wanted longer distance range than 1.5 meters, but when it comes to selecting items, most answered that a 1 meter range was sufficient.

We asked the users if they were comfortable with letting the system predict what the user is interested in using the data gathered from natural interactions. All of the users answered that it is helpful when they do not have their mobile phones out of their pocket, and they agreed that it would help them to log information that was out of their attention. Yet, the users commented that they could not fully rely on the system's intelligence to filter their data while not providing any feedback to the user. Besides, the users did not want excessive data to be gathered in their system. Some answered that they would like a secondary method (e.g., selecting from the screen, or explicitly scanning the item) to ensure that they have 'bookmarked' the specific item of interest.

## 5.3 Other Discussions

### 5.3.1 Health issues

Following the enormous increase in the use of wireless mobile telephony, there have been questions about whether exposure to electromagnetic fields (EMF) raises health effects. The frequency spectrum for the UHF RFID (902~928MHz) is similar to the mobile-phone carrier frequency (GSM850: 824–849MHz, GSM900: 880–915MHz), where FCC prohibits transmitting a power over 36dBm (4watts) in this frequency range. Our system is configured to emit a maximum of 33dBm (2watts) power, which is also the maximum transmit power of a typical GSM mobile phone. Although the effect of EMF has not been explicitly described, the World Health Organization defines the EMF as a potential risk and recommends the exposure to be "As Low as Reasonably Achievable" (ALARA) [32].

During the experiments, we kept the EMF intensity of the Infofield lower than that of a mobile phone, which we may consider an acceptable amount. First, we restricted the maximum transmit power to the level of a GSM mobile phone. Second, the antenna is positioned near the waist and the minimum distance was limited to 10cm from the body, whereas a mobile phone, it is normally placed near the head of the user while in use.

Third, a reflector is placed behind the reader to block the flux that heads directly to the body (this also enhances the performance of the antenna, but makes it directional).

### 5.3.2 Privacy

The EPC introduces a pair of privacy threats: tracking people by using the unique IDs of EPC tags secreted on their possessions, and inventorying their possessions without permission. When an EPC reader asks the tag for its data, the tag must respond to the request. This process implies that the data of our personal tags can be exposed without us controlling how the data will be used. In addition, a tag's trail can be tracked both in time and space by looking into the RFID network. An expensive item in the pocket can be detected by a malicious reader. Even if the person carries only items that are of little value, the tags' responses can be used to track the person.

In the scenario that the Infofield proposes, users carry private readers to monitor the environments. This scenario holds less privacy issues than previous RFID systems where the users possess tags that can be tracked by the RFID network. However, the privacy threats may also occur among the private readers in the scheme that we proposed; the other private readers can still inventory your items. The demonstration in this thesis was carried out in a public office, assuming the objects were opened to the community. But in a typical situation where there are multiple users, there is a need for a protection mechanism to secure private belongings.

Related works on the privacy protection have been explored with the OpenTag [19], the predecessor of SensTag. With OpenTags, we have applied a hash chain algorithm that makes the tag reply a different ID (pseudo-ID) whenever a reader tries to read the tag. Generated using a publicly known algorithm, the sequence is forward secured. Thus only readers that know the initial seed can associate the serial numbers in the sequence with the identity of the tag. Since the actual identification of the tag is not publicly known, the hash chain method prevents unwanted identification of tags. This feature can be added to a SensTag for better security.

# Chapter 6

# Contributions & Future Work

## 6.1 Contributions

The previous chapters in the thesis have described the development of Infofield, from the motivation, through hardware, firmware, and the user interface design, to testing in lab environments and user evaluations. The read range of the technologies that were used in previous research was either too short or too long. In a short-ranged system, the user had to explicitly point or scan the object to retrieve the information. On the other hand, a wireless module such as Bluetooth, which had a longer range, provided ambient detection of the surroundings, yet was not applicable to daily items due to its costs. In this work, we used the UHF RFID system which was a mid-range, cost-effective system capable of multiple detections and also had the potential to replace barcodes in the near future. The EPC protocol, which works in the UHF range, had been developed lately and not been fully explored in the manner that Infofield proposes.

In contrast to a supply-chain metaphor that indirectly infers the interaction between the user and the items by monitoring the tagged users and objects with a grid of RFID readers, the Infofield gives a mobile RFID reader to each user for detecting his or her own environment to ensure better privacy and to provide user-centric data.

We have demonstrated a novel approach of using a preexisting UHF system; instead of deploying RFID readers which track the users, the users carry mobile RFID readers to scan their environment. A unique contribution of our work is that our system can be absorbed into an existing infrastructure. In addition, we have proposed tangible mechanisms to solve the singulation problem in a one-to-multiple interaction scenario, using low-power sensors on the RFID tags.

This thesis envisions personal, pervasive scenarios using the EPC-compliant tags, and we hope our work will influence the next generations of EPC protocols, which is yet mainly focused on the supply chain usage. The result of our work would contribute to future research which seeks to develop a similar wearable device.

## 6.2 Future Work

Technical challenges of the system still remain. Being a very power constrictive system, the performance of the RFID system was heavily affected by the amount of power we could afford. To balance between the power and the performance, we had to modify our tags to be battery powered. Still, we were able to test and evaluate the sensors that we used to determine that they could extract the daily activity of the users, and that the power consumption was low enough to be embedded into passive RFID tags. Also, the RF characteristic of SensTags needs to be improved for better performances. The impedance of a SensTag's antenna was dynamically affected by body effects, but finding the optimal impedance was beyond the scope of this thesis.

For a seamless demonstration, there are still needs for better hardware performance and an environment with a larger number of RFID tagged objects. Also, to be truly unobtrusive, the system needs to be more compact and should have a higher read rate plus a better user interface. Preliminary user studies were conducted to analyze the effectiveness of the user interface, but were limited because some scenarios were impractical due to the unstable RF performance of Infofield. With increased performance, we look forward to demonstrating a large scale, multiple user application with the Infofield system.

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# Appendix A

These are PCB layouts of the SensTag.

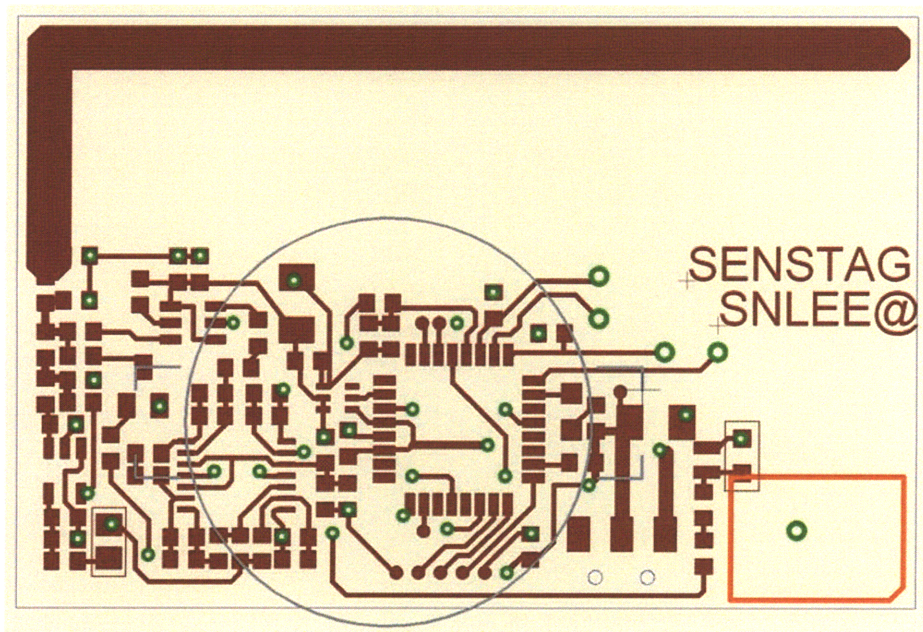


**Figure 30: SensTag PCB layout (top).**

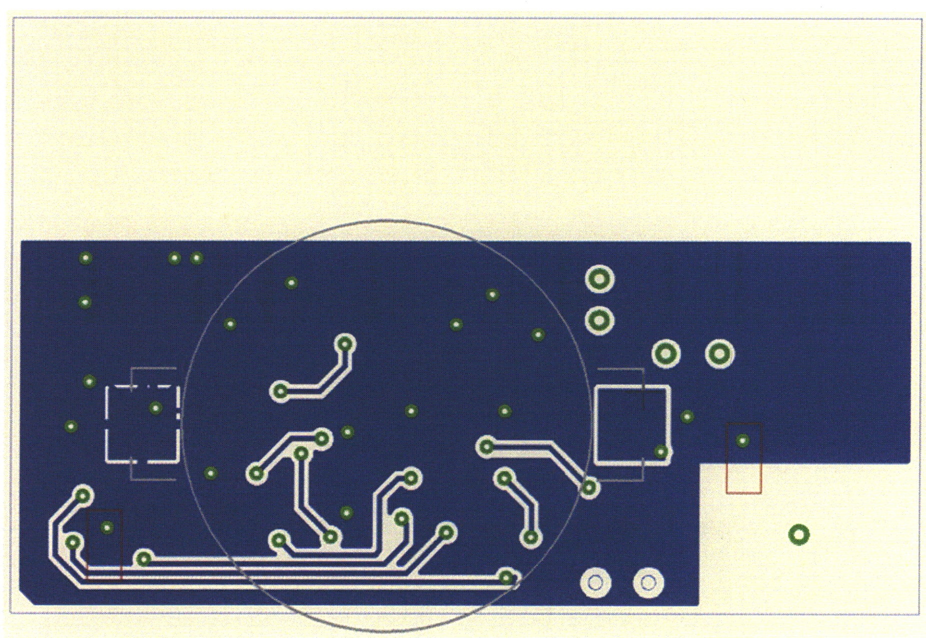

**Figure 31: SensTag PCB layout (bottom).**

# Appendix B

Followings are the measurements from the Mercury 4 RFID reader. The exact sampling rate varies with the testing environment.

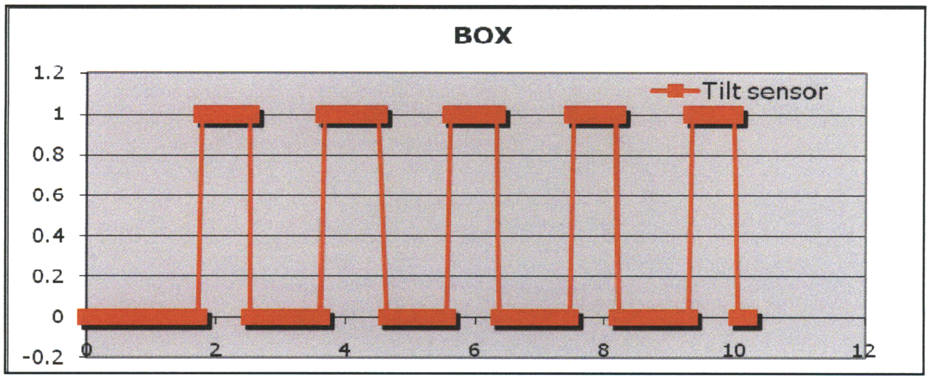


**Figure 32: Data from Mercury 4 (20 samples/sec) – The user was asked to flip the box and back 5 times.**

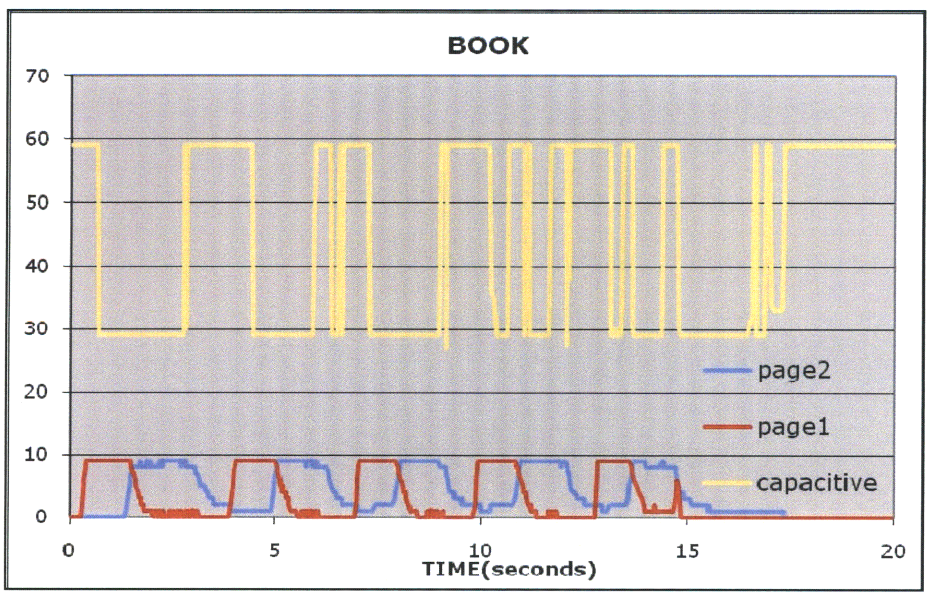


**Figure 33: Raw data from Mercury 4 (40 samples/sec) – The user was asked to repeat 'flip to page 1','flip to page 2', and 'close the book' 5 times.**

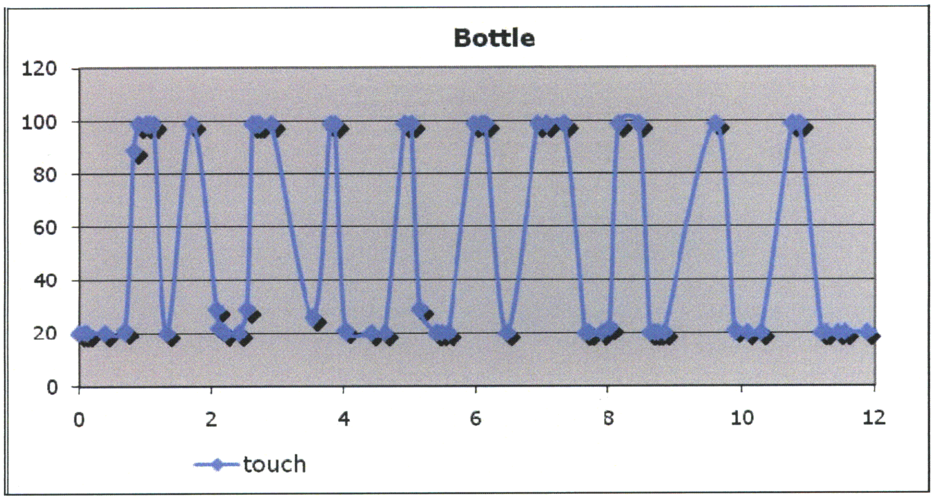


**Figure 34: Data from Mercury 4 (8 samples/sec) – The user was asked to touch the bottle 10 times in a row.**

# Appendix C

## User evaluation template

In this experiment you will be asked to wear an RFID reader and interact with the following objects.

- A box: touch, open, or flip the box
- A book: touch, open to page1 or page2
- A bottle: touch

**1: Test A**

The items are located in your vicinity; the system will pop up the image when the items are near you. Please bring them to the desk.

**2: Test B (x 2)**

Please perform the 13 tasks listed on the instruction in their listed order. Your activities will be analyzed by the system. Imagine you are actually using the items. Please give at least few seconds before moving on to the next tasks. Normally a whole cycle takes about 2~3minutes to finish the tasks.

**Instructions**

1. Pick up the bottle
2. Leave the bottle on the desk
3. Pick up the book
4. Open page1
5. Open page2
6. Close the book
7. Leave the book on the desk
8. Pick up the box
9. Open the box
10. Close the box
11. Flip the box upside down
12. Flip the box right up
13. Place the box down on the desk

**3: Test C (x 2)**

Repeat Test B, but this time the mobile screen will give you feedback on what you are doing. When you see that the photo on the screen matches your activity, move onto the next task. If the photo on the screen does not change for more than 5 seconds you may skip the current step and move on.

**4: Test D**

Feel free to play with the object, and monitor how the system responses to your activity. If you are done, we would like you to answer the following questionnaires.

1. The Infofield system records every event that happens through the day. Similar to the history in your browser, the history is tagged with time and location. Suppose this system is embedded in your phone, would you like to keep the history of your physical activities? What could be a good usage for it?

2. This system automatically detects the items around you, improving the awareness of your surroundings. The range of this system is approximately 1~1.5m. Do you think this is appropriate? If not, what will be a range that best cover your interest?

3. A longer range gives you more information, but it gets harder for the system to explicitly pick out what you are interested in. When multiple items are detected, following method could be used to specify the item you are interested in.

   A. All items near you are listed on the screen. You select the item to get further information.

   B. When you manipulate the object in a natural way (e.g. touch, open, and turn), Infofield presents you the linked information with the object you are currently engaged in.

   C. Explicitly place a mobile phone over the tag to retrieve information. (Somewhat like your T-pass; beep!)

Which would you prefer of the three? Why?