

RFID Light Bulb: Enabling Ubiquitous Deployment of Interactive RFID Systems

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Radio-Frequency Identification (RFID) technology has the potential to provide inexpensive, wireless, battery-free connectivity and interactivity for objects that are traditionally not instrumented. However, these systems have not seen widespread deployment outside warehouses and supply chains, owing to the complexity of installing bulky RFID readers, antennas, and their supporting power and network infrastructure.

In this work, we leverage advances in semiconductor optics, RF antenna design and system integration to create a hybrid RFID reader and smart LED lamp, in the form factor of a standard light bulb. This makes deploying RFID readers literally as easy as screwing in a light bulb. We explore the home-scale RFID interactions enabled by these smart bulbs, including infrastructure monitoring, localization and guided navigation, and standalone lighting effects.

CCS Concepts: •**Human-centered computing** → *Ubiquitous and mobile computing systems and tools*; •**Networks** → *Wireless access points, base stations and infrastructure*;

Additional Key Words and Phrases: Interactive RFID; Battery-free Sensing; infrastructure monitoring, light bulb, UHF RFID

ACM Reference format:

Jeremy Gummesson, James McCann, Chouchang (Jack) Yang, Damith Ranasinghe, Scott Hudson, and Alanson Sample. 2017. RFID Light Bulb: Enabling Ubiquitous Deployment of Interactive RFID Systems. *PACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 2, Article 12 (2017), 16 pages.
DOI: <http://doi.org/10.1145/3090077>

1 INTRODUCTION

Low-cost sensors that can be ubiquitously deployed in our indoor living environments are a core building block needed to enable many HCI applications. Typically they take the form of matchbox size devices that have batteries, wireless communication capability, and stream high-fidelity sensor data such as 3D acceleration to a wireless gateway for aggregation and post processing. While many research efforts have shown that these types of wireless sensor nodes can be successfully used for activity inferencing in the home [23, 38, 41], their relatively

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2474-9567/2017/6-ART12 \$15.00

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DOI: <http://doi.org/10.1145/3090077>

Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, Vol. 1, No. 2, Article 12. Publication date: June 2017.

large size, high per-unit-cost and need for battery maintenance and replacement becomes prohibitive when deployed at scale.

An alternative approach that has recently emerged is the use of passive RFID tags as low fidelity sensors. UHF RFID tags have the advantage that they are readily available in thin “sticker” form factors, are battery free since they harvest all the energy they need for operation from RFID readers, and are low in cost at 7-15 cents when purchased in volume [22]. Recent work on interactive RFID systems has shown that these simple tags can be turned in to a variety of different sensors by analyzing changes in the low-level communication channel parameters between the tags and reader. Applications include human object interaction detection in the home and work place [18, 20], battery free user interfaces [17, 37] and human robotic interaction [19].

While these research efforts have shown that passive RFID tags can overcome many of the limitations of battery powered sensor nodes, the relatively short read range of UHF RFID tags – 5-6 meters for typical indoor environments – introduces its own deployment and scalability challenges by requiring the placement of several RFID readers in a large room. While the installation of one or two readers is manageable in office environments with drop ceilings [18]. The large scale deployment of RFID readers throughout a home or office building can be a massive undertaking [43, 44], as each reader and antenna must be mounted and electrical power and Ethernet must be run to each reader.

To address these limitations, we designed an RFID Light Bulb (Figure 1): a Wi-Fi-connected smart LED bulb that contains an integrated RFID reader and antenna. Our bulb can be installed in place of a traditional lamp, making it easy to create networks of RFID readers in any space with indoor lighting. In addition, the integrated RGB LED lamp provides a natural channel for feedback to users.

In order to demonstrate the potential of our RFID light bulbs, we’ve built several home-scale applications on a test deployment of the bulbs. Our infrastructure monitoring example shows that the bulbs can be used to perform standard house alarm and monitoring functions without batteries. Our localization and navigation examples use the bulbs to assist users in locating lost objects and finding their way around buildings. And our packaged content examples show how books, toys, and games can come with built-in custom lighting effects.

In summary, the main contributions of this work are:

- The hardware design and integration of an RFID reader with an LED smart bulb.
- Prototype whole-house interactive RFID applications that demonstrate the effectiveness of our bulbs.

2 BACKGROUND AND RELATED WORK

Lighting is one of the most ubiquitous resources deployed in human-occupied infrastructure. In this work we demonstrate how we can exploit the AC power infrastructure and natural line-of-sight placement of lighting units as a means of naturally distributing RFID reader infrastructure in areas of interest.

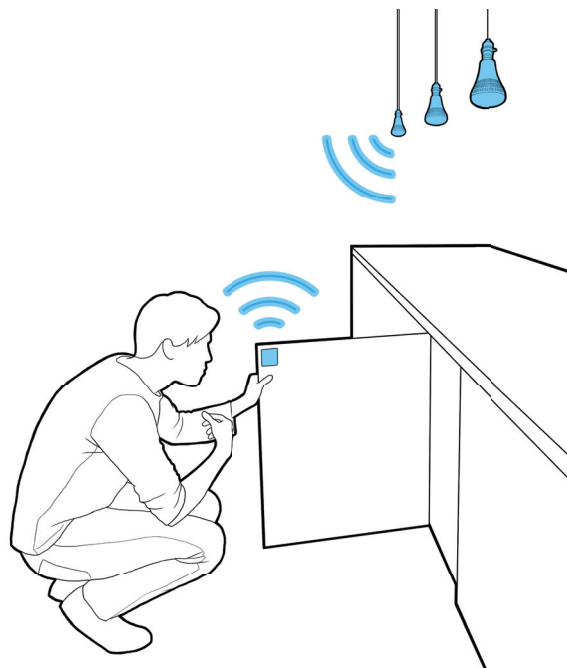


Fig. 1. RFID light bulbs enable seamless interactions with tag-augmented infrastructure, people, and objects.

We are not the first to consider deploying RFID readers along with lighting infrastructure [25, 32]; however, our bulb is the first to fit the entire reading apparatus *inside* the bulb. In contrast, the MonsoonRF company's commercial implementations [25] rely on components outside the bulb itself – the “LANTERN-T” is a track light fixture which surrounds a conventional bulb with an antenna and reader circuitry, while the “LANTERN-S” appears to be a bulb with external antenna – though no further details are available. Our integrated RFID Lightbulb platform is the first example of a self-contained RFID reader that includes dynamic RGB LED lighting and can be deployed anywhere a conventional light bulb can be installed.

More broadly, the “Internet of Things” (IoT) has attracted significant attention in recent years, with many types of devices coming to the consumer market. Examples of these devices include, door locks, security cameras, thermostats, voice-based personal assistants, and even simple buttons that automate internet retail purchases. Bluetooth Low Energy, Zigbee, and Wi-Fi are all examples of networking technologies that connect these different classes of devices. RFID is complementary to these radio technologies, because it is a passive radio technology; while RFID has relatively lower throughput, tags do not need batteries for power – they can be implemented as flat labels that require zero maintenance after installation. Previously, RFID readers have not seen widespread deployment in interactive environments due to their cumbersome nature and cost; RFID light bulbs provide the missing link for connecting passive IoT devices.

In exploring the potential widespread use of RFID technologies, a number of systems have considered sets of base techniques for use of tags as sensors and input devices. For example the use of modified RFID tags for battery-free buttons and other input devices was considered in [1, 11, 24, 35]. In more advanced work, the Wireless Identification and Sensing Platform (WISP) [33] provided custom-built RFID tags with an embedded micro-controller, enabling a wide range of sensing and input applications (however, at significantly higher costs than off-the-shelf RFID systems).

Unmodified RFID tags have also been employed for input sensing such as tracking the currently open page of a book [2, 3] and sensing liquid level in a container [4]. More advanced techniques have also been able to use off-the-shelf RFID tags for sensing of tag motion both in limited forms [9] and in a more robust fashion [18]. Recent work has expanded on these approaches to create a range of inexpensive paper input devices using unmodified tags [17] and to improve the response times for that type of sensing by using probabilistic techniques [37].

Other work has considered applications that might be enabled by the low-cost, wireless, and battery-free nature of RFID systems. Early work considered using the identification capabilities of RFID tags to link physical objects to virtual content (see for example [42]). Later work has expanded into areas such as person and object tracking and localization [5, 8, 30], as well as activity recognition [6, 26, 29], and applications such as finding objects [16, 34].

RFID-enabled light bulbs build on all of this prior work; they enable the previous applications and frameworks while also enabling new classes of applications and interactions that can monitor the infrastructure of an entire building or track objects and people as they move between arbitrary indoor locations.

3 TECHNICAL OVERVIEW

The technology ecosystem surrounding a deployment of RFID light bulbs also comprises tagged objects and people, signal processing software that detects tag presence and movement, and a programmed set of interactions. Here, we provide a technical overview of each of these core components required for ubiquitous interactions with a network of RFID-enabled Light bulbs.

As shown in Figure 2 (left), our RFID light bulbs are deployed by screwing them into standard Edison-style (E26) lighting sockets. Each bulb includes controllable LED lighting, an integrated RFID reader and antenna, and a Wi-Fi radio. We discuss the design and capabilities of the RFID light bulb in greater detail later in the Hardware design section.



Fig. 2. An interactive RFID system consists of, left-to-right, readers (e.g. our light bulbs), tags, and software to interpret tag information.

Objects of interest, people, pets, and infrastructure augmented with RFID tags (Figure 2, center) can be detected when passing in the vicinity of one of the installed light bulbs. As described later, specialized sensor tags, as well as simple augmentations of standard tags, can also be used to implement sensors and input devices for interactions that go well beyond the mere presence or absence of objects.

Software running on each of our RFID light bulbs repeatedly reads all tags in the local environment, and reports data about the detected tags via Wi-Fi. Additionally, the bulbs listen for color change commands, and fade their LED brightness accordingly. Application software running on a host computer interprets the reads from all bulbs and – at its discretion – sends them lighting commands. We describe this in more detail in the software section.

3.1 Hardware Design

Our RFID-enabled light bulb unit was implemented within the form factor of a standard BR30 floodlight. This design was adopted because it allows for deployment anywhere there is a standard light socket. In this section we will give a brief overview of the critical design components.

An overview of the mechanical design of the light bulb is shown in Figure 3. The enclosure that houses a light bulb's internals was fabricated using a 3D printer. A light diffuser is mounted on top of the bulb and vent openings are placed around the edges to allow the dissipation of heat.

Inside the light bulb, electronic components are mounted as a stacked board assembly that is suspended from a lip at the top of the enclosure (Figure 3). The RFID light bulb has the potential to generate substantial heat; two fans are mounted on either side of the middle board (LED driver board) and used to force heat generated by the CPU, RFID reader, and LED drivers out the vents in the sides of the light bulb enclosure.

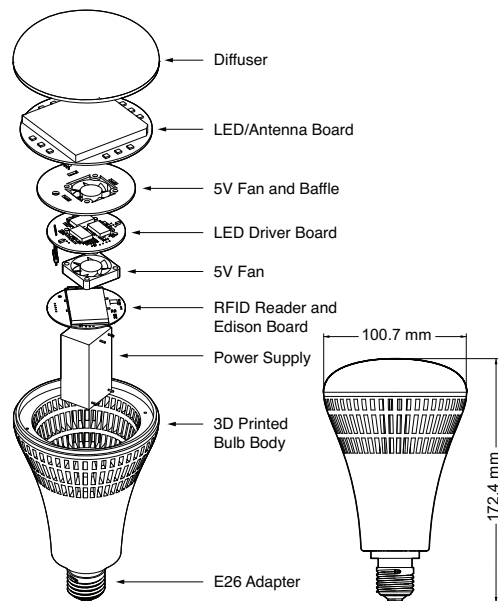


Fig. 3. The RFID light bulb is housed in a 3D printed enclosure. The stacked board assembly is designed to force heat through vents on the side of the enclosure. The entire light bulb is same size as a BR30 floodlight.

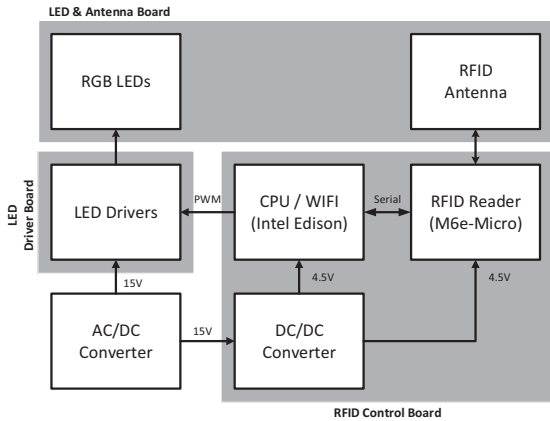


Fig. 4. An electrical block diagram of our bulb. The internal components are split across three circuit boards (grey boxes).

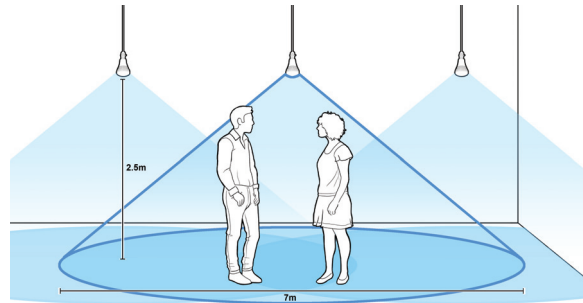


Fig. 5. The directional patch antenna provides a read range of ~4.5 meters over a 120 degree cone, resulting in a read diameter of 7 meters when hung 2.5 meters from the floor.

A block diagram of the electrical components of the light bulb is depicted in Figure 4. An AC/DC converter in the base of the light bulb provides a stable DC supply voltage to the rest of the system. An Intel Edison Compute Module [15] controls all components of the light bulb and provides network connectivity via Wi-Fi. In particular, the Edison is responsible for PWM control of the LEDs and serial control of the RFID reader.

The RFID reader [40] used in our system occupies a small form factor and is optimized for embedded applications; despite its small size, it can transmit at a full Watt of power and supports the Full Gen2 UHF RFID protocol [10].

The reader antenna we use is a 5 dB gain directional patch antenna. When optimizing an antenna design for read range, there is a fundamental trade-off between size, power, and bandwidth. Since we are constrained by size (light bulb form factor) and power (FCC limits), we approximately meet the bandwidth requirements for a functional RFID system while maintaining antenna performance within the space constraints. This was accomplished by designing a novel custom UHF RFID antenna on a high dielectric ceramic substrate, that incorporates the RGB LEDs and wiring, and uses a specialized Pi match tuning network to overcome issues with the reduced ground plane size.

The per-frequency read performance using this antenna tuning approach can be seen in Figure 7. Here, we depict the 50 channels used by the Gen2 RFID protocol, and show the fraction of reads received per channel during a normal inventory round when transmitting at

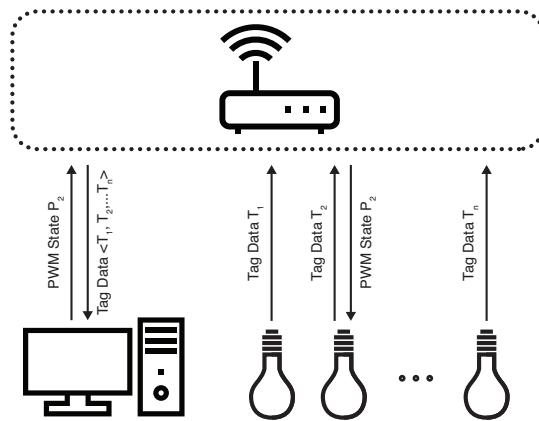


Fig. 6. RFID light bulbs communicate with a host computer via Wi-Fi. Tag reads are broadcast over UDP, and light control information is received via TCP.

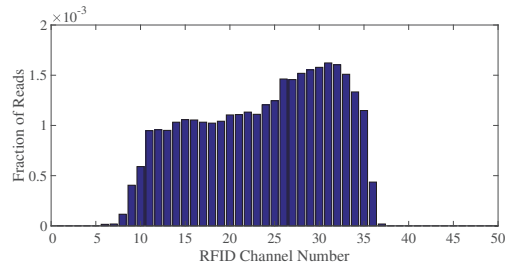


Fig. 7. To compensate for size and power limitations, we optimize the RFID light bulb’s antenna for performance across roughly 50% of the channels used by the Gen2 RFID protocol. This results in some dropped reads, but longer communication range.

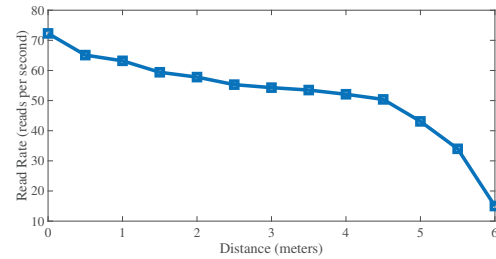


Fig. 8. Tag read performance varies as a function of the distance from the reader. When varying the distance of a tag from the ceiling-mounted reader, we observe that tag read rates decrease with distance.

1 Watt of power to a tag at a distance of 2 meters – tag reads are approximately even amongst the frequencies within the tuned bandwidth, but those outside the tuned range are dropped.

With this antenna tuning configuration, the light bulb achieves 50 reads per second at ~4.5 meters of read range in a 120 degree cone-shaped area below the light bulb (Depicted in Figure 5). To understand how tag read performance varies as a function of the distance from the reader, we deployed a tag near the floor at varying distances from the RFID light bulb; this distance is represented by the diagonal line depicted in Figure 5. In Figure 8, we observe that tag read rates slowly decrease with respect to distance. Beyond 4.5 meters of read range, read rates quickly diminish because the tag moves outside of the antenna’s directional coverage.

Theoretically it is possible to achieve higher read rates, but performance is thermally throttled with our current hardware and cooling solution. RFID light bulbs should be able to support a variety of applications and should be able to interface with a variety of different tag types in different orientations; we found that tags with antenna topologies including patch and dipole meander can be read in orientations ranging from horizontal to vertical with respect to the light bulb antenna, while still achieving sufficient read performance to enable our target applications.

The LEDs used in the light bulb are both high-efficiency and high-power [7]. A series arrangement of 4 LEDs for each RGB color channel are mixed using a 3D printed diffuser at the top of the bulb. The target flux for our lightbulb is 650 lumens, which matches that of a BR30 floodlight. We found that our light bulb can achieve 531.39 lumens with all 3 color channels at 80% duty cycle – this is the maximum duty cycle that our power supply can handle. Due to the thermal envelope of our prototype, we limit the LEDs to a 50% duty cycle and achieve a flux of 308.36 lumens.

3.2 Software Design

The Intel Edison runs a customized version of the Yocto embedded Linux distribution [21]. The bulbs are pre-configured to connect to a wireless router with a given SSID (depicted in Figure 6), and are assigned a static IP address by the router. The bulb’s internal clocks are synchronized with a Network Time Protocol (NTP) server – this allows any RFID read events to be globally time synchronized. In our prototype deployment, the IP addresses were configured by hand on the router; though this would be straightforward to automate.

Each bulb runs two servers (written in C++) that provide the core functionality required by an RFID light bulb. The “RFID Server” reports tag data via UDP broadcast and the “PWM Server” receives commands from a remote client to modify the light state of the bulbs. At boot time, the Intel Edison starts executing these two servers as background processes. We now describe these applications in more detail.

3.2.1 RFID Server. The first application, called “RFID Server”, is responsible for configuring the RFID reader and receiving data from tag read events and relaying them over the wireless network. The application communicates with the reader using a manufacturer-supplied API, which sends and receives data over a serial port. When the application starts, the reader is configured using the values shown in Table 1. We optimized these read parameters for high read rates from a relatively small number of tags per reader while remaining resilient to multipath interference. After this reader configuration completes, a pre-programmed *read plan* is placed in the reader which specifies how tags are queried. Queries are performed in a repeated series of *tag inventory* rounds which attempt to read each relevant tag that is within range. This read plan also handles additional commands necessary to read specialized sensor tags.

Reader Parameter	Value
Transmit Power	30 dBm
Reference Interval (TARI)	6.25 μ s
Backscatter Link Frequency	250 KHz
Tag Modulation	Miller 2

Table 1. The reader configuration parameters used by our light bulb.

The first part of the read plan queries the IDs of conventional static tags. The second part of the read plan specifies the special commands necessary for reading sensor tags (*e.g.*, to read temperature data from the user memory of a specialized thermometer tag). These two portions of the read plan run at a ratio of 10 to 1 respectively.

After the read plan is established, the reader continuously reports any tags found that satisfy the specified constraints. Each individual read event is reported as a single broadcast UDP packet; the data fields provided by these read events are depicted in Figure 9. The physical layer data exposed by these events supports the use of previously developed RFID interaction systems such as RapID[37], PaperID[17], and IDSense[18].

We chose to use broadcast UDP so that any device on the local area network can listen to the streams of tag data generated by the light bulbs and run RFID-aware applications. Since UDP packets may be reordered, duplicated, or dropped, sequence numbers are included in the packets, and applications ignore duplicate or out-of-order reads. We assume that the local area network has been properly secured and no malicious adversaries are present that sniff the RFID packet streams. In other environments, additional precautions may be necessary (which should be easily implemented using the on-board computing available to the bulb).

3.2.2 PWM Server. The second application, called “PWM Server,” controls the state of a light bulb’s LEDs. The application listens for commands on a TCP port. Commands are simple 4-tuples: <Red, Green, Blue, FadeSec>, where Red, Green, and Blue are floating point values between 0 and 1 that represent the intensity of each color channel and FadeSec is a floating point value in seconds that specifies the timing of the color transition of the previous state to the state specified by the command.

3.3 Using Tags for Input and Interaction

RFID tags have been designed for the primary purpose of reporting a unique identifying number for each tag. However, special purpose (but readily available and inexpensive) tags are also available which can return simple sensor data such as temperature. Further simple augmentations, along with specialized read techniques, can turn

RFID Read Data:

255.255.255.2555	192.168.1.101:8888	<96 bits>	143 degrees	-62 dBm	915000 KHz	22.0 C	<64 bits>	<32 bits>	55.0 C
Destination IP	Source IP	EPC ID	Phase	RSSI	Frequency	Tag Temperature	Tag Read Timestamp	Tag Read Seq Number	Reader Temperature

Fig. 9. An example of the read data broadcast over UDP by our bulbs. Channel parameters (phase, RSSI, frequency) are included so that applications can perform tag state estimation.

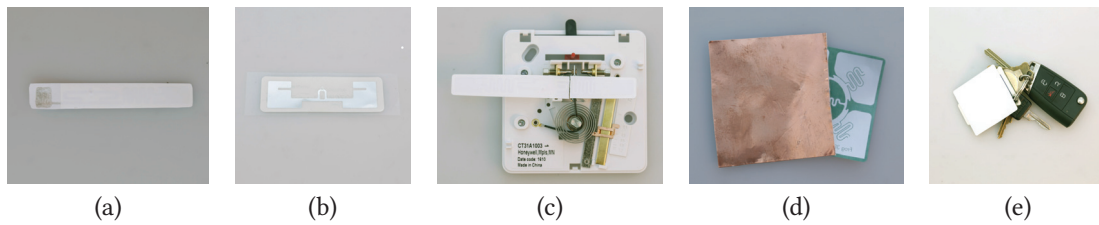


Fig. 10. The RFID tags used in our interactions go beyond simple identification. Examples of tags implemented include a) touch sensitive buttons, b) thermometer tags, c) augmented thermostats, d) contact switches, and e) augmented objects such as keys.

standard tags into simple input devices or sensors. In this section we review some of the ways this can be done (Figure 10). (For additional details, see for example [17, 18, 37]).

3.3.1 Touch Sensitive Buttons. Using the technique introduced in [17], a touch sensitive button can be constructed from an ordinary tag using a specially designed (but easy to create) antenna pattern made with conductive ink on paper. This asymmetrical pattern is capacitively coupled to the underlying tag to augment its existing antenna trace. In its base state, this asymmetrical antenna de-tunes the tag and causes it to become unreadable. However, if the user presses (and capacitively couples to) a special conductive patch on the augmentation, they essentially form the other half of the antenna and the underlying tag becomes readable again. Hence from the reader's perspective, the tag responds with its ID while being touched, but does not otherwise.

Touch sensitive buttons were implemented using Alien ALN-9640 Squiggle Tags [39]. When activated by a user's touch, we observed an average read rate of 45 reads per second when placed on a wall approximately 3 meters from the light bulb. This level of performance provides sufficiently low latency to enable a variety of interactions that provide nearly immediate feedback to the user.

3.3.2 Thermometer. Temperature sensing can be performed with a commercially available special purpose tag that contains an RF-powered thermistor. These tags are accessed in two passes. At the beginning of each tag inventory round, a specialized select command is issued that instructs the tag to query its internal temperature sensor and store the value in its local memory. A second query is then performed later in the inventory round to issue a read command returning that value.

Thermometer tags were implemented using RFMicron RFM3200 Temperature Sensors [31]. Since two rounds of inventory are required to collect the sensed values, this procedure results in an end-to-end latency of more than one second. This level of performance is more than sufficient for typical monitoring applications in residential settings.

3.3.3 Contact Switch. A third type of tag augmentation can be used to create a contact switch. A contact switch is implemented using a piece of metallic foil and a standard tag. To close the switch, the tag's antenna is covered in foil and cannot be read by a reader. To open the switch the foil is removed, and is read by a reader. This type of tag is especially useful for monitoring the state of fixed infrastructure. In some cases, an object's structure can act as a Faraday cage surrounding the tag when a door is closed (i.e. refrigerator or washing machine) and obviates the need for an explicit foil covering.

Contact switches were implemented using SmartTrac Frog 3D RFID tags [36]. These tags were selected because of their small, square form factor, simplifying the placement and sizing of the metallic cover. The antenna design also allows for more diversity in tag placement, resulting in read rates of approximately 50 reads per second

at distances up to 4 meters in a variety of orientations. This results in near real-time detection of changes in infrastructure state.

3.3.4 Thermostat. A fourth tag augmentation consists of a tag cut into two parts which are then attached to a modified mechanical thermostat. The thermostat is set by a user, using a conventional slider that specifies a temperature set point. When the ambient temperature falls above or below the set point a metal arm toggles positions to change an electrical contact normally used to actuate a heating source. In our augmented tag, this internal movement modifies the distance between the tag IC and the cut portion of its antenna allowing them to be more or less capacitively coupled. The distance between the two tag portions manifests as a change in detected read signal strength (*RSSI*) and read rate that can be used to determine the state of the thermostat.

We implemented the thermostat tag using a Honeywell CT50K Low Temperature Thermostat [12] and an Alien Squiggle tag. We observed that the mean *RSSI* of tag reads was -55 dBm while the thermostat arm is in the ‘closed’ position and -70 dBm while in the ‘open’ position when deployed on a wall at a distance of 2.5 meters from an RFID light bulb. We note that the deployment of such a tag would need a one time calibration to determine the thermostat state from these values, which will vary according to the specific setup.

While highly specialized, the thermostat augmentation provides an exemplar for how a variety of mechanical motions might be sensed in a power-free fashion with RFID tags.

3.3.5 Location. An additional capability that can be provided is localization of tags. A standard tag fixed to an object, person, or animal can be tracked by associating the read event with the network address of a particular RFID light bulb. In the case the tag is read by multiple readers, its position can be further discriminated using multi-lateration. This technique combines the *RSSI* and phase information from a single tag observed by multiple readers; using this combined information, a tag can be located within a smaller region between the deployed RFID light bulbs.

4 APPLICATIONS

In this section, we present a variety of interaction experiences that are uniquely enabled by RFID light bulbs; we break these interactions down into several distinct categories that take advantage of ubiquitous RFID reader deployments and instant light-based feedback. In Figures 11-15, we show several of these applications that range from home monitoring applications to lighting effects programmed into tags embedded in objects.

The programs that power these interactions run on a host PC attached to the same wireless network as the bulbs (Figure 6). The PC listens for UDP broadcast read events and sends PWM control messages to the bulbs over this network. In a consumer deployment, we envision that this computer might be integrated with the wireless hub for the bulbs, providing a single-box solution.

4.1 Localization

Software that wants to determine the location of a tag can simply record which reader sent it information about that tag most recently. This allows a tagged user or item to be localized to the area under a light bulb’s RFID antenna.

4.1.1 Light-Assisted Navigation. Traditional navigation applications present the location of a user as a symbol on a map. Using RFID light bulbs, we can instead guide a user to an indoor location by changing the state of RFID light bulbs deployed around the infrastructure. This example is depicted in Figure 11.

In this scenario a user wears an RFID tag on their person. The interaction begins when the user selects an icon corresponding to their keys on their mobile phone. The server running the interaction example is provided with a configuration file containing the layout of the RFID light bulbs. It uses this information to guide the user toward their goal by flashing the bulb near the user that is closest to the item the user wishes to locate. As the



Fig. 12. In this interaction, a user presses the quick-cook button on a microwave augmented with a touch sensitive tag. An RFID lightbulb in the user’s office flashes to notify the user of the microwave timer has expired.

user enters the read area of the flashing bulb, the new closest bulb begins to flash, and the process continues, leading the user to the bulb over their chosen item – in this case, the lost keys.

4.1.2 Ambient Contextual Timers. Many common household tasks require the use of a timer in conjunction with a machine to inform a user that a particular activity has completed (e.g. microwave, washer, dryer, dishwasher). While the non-blocking behavior of household appliances frees up residents to engage in other activities, it is common that the assigned task may be forgotten (i.e., a person washing their clothes forgets to move washed items to the dryer and they become moldy).

The user experience surrounding the timing of these household tasks can be greatly enhanced by a network of RFID light bulbs. In this example, the timer button of a microwave in an office kitchen is augmented with an RFID touch sensitive button tag (microwave and user shown in Figure 12). Upon pressing the button, a timer starts in the server, set to expire at the same time as the timer in the microwave. The user of the microwave, who is wearing an RFID tag on a lanyard, is identified as the person who pressed the button since they are in front of the microwave during the button press.

The user moves back to their office after starting the microwave and their location is known since their tag is read by an RFID light bulb above the desk in their office. After the timer running in the server expires, it sends a message to the office light bulb to flash several times, indicating to the user that the microwave has finished its cooking cycle. This experience requires zero additional effort by the user and provides a subtle reminder of timer completion.



Fig. 11. In our localization solution, flashing bulbs lead the user to their chosen item. In this case the user tells the system to lead them to their keys.

4.2 Infrastructure Monitoring

Another class of application that benefits from deployments of RFID readers are those that involve the monitoring of infrastructure. Many aspects of building maintenance and security can benefit from RFID augmentation. The state information provided by RFID tags can subsequently be used to actuate building resources.

We built an example application which monitors the state of a room using a combination of RFID tags to detect movement of infrastructure (e.g. doors, windows, thermostat) and tags that quantify temperature of particular locations within a room (depicted in Figure 13).

In our deployment of this application, we instrumented a kitchen with a variety of tags. We equipped one drawer and three doors with contact switches; the drawer and one of the doors did not require foil covering for the switches, as the counter top and door frame are metal and naturally block tags from communicating with the light bulb readers while closed. The ability to track the state of doors in real-time can be used to reduce home energy consumption by minimizing waste, used to track occupancy and movement within a building, and may also be used in home security applications for intrusion detection.

We also deployed a thermostat and thermometer tag, co-located on an interior wall of the kitchen. The combination of information provided by these two tags provide remote access to the temperature thresholds used by the HVAC system and the overall temperature profile of the room over the course of the day. While this approach still requires the thermostat set point to be manually configured, this allows a home energy heating profile to be tracked autonomously by augmenting existing infrastructure with relatively cheap tags. With a trivial amount of effort, additional thermometer tags could be deployed to build up a more fine-grained temperature profile of a home.

The information provided by the tag is aggregated by a central server and is fed into an infrastructure dashboard application that displays the open/closed state of doors, the instantaneous temperature of several thermometer tags, and the current state of the heating system using the thermostat tag (Figure 10 (c)).

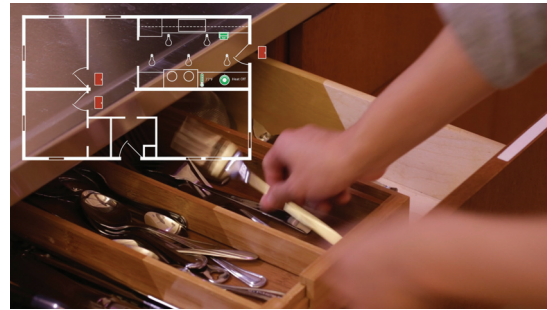


Fig. 13. RFID lightbulbs enable whole house infrastructure tracking. In this interaction example, we monitor the state of a kitchen in a dashboard application.

4.3 Prepackaged Content

Simple interactions with our bulbs can be written directly into the tag's 96-bit Electronic Product Code (EPC). Such tags can be programmed in batch at a factory and added to a product to provide an enhanced lighting experience for a negligible increase in cost. The ability to interpret these special *prepackaged content* EPCs is built into the bulb control software, so – from the users' perspective – the added functionality “just works”, requiring no application downloads or external software.

The EPC format we use for these tags (Figure 14) consists of a one-byte header, followed by five bytes describing the comparison to perform, one byte giving action priority, one byte describing the action to take, and two 16-bit (5:6:5 rgb) light colors. The possible comparisons include comparing the current time or an arbitrary byte or word of tag data to a reference value. (This last option is convenient for sensor tags, which often use tag data to report sensor readings.) The action describes how the light should change based on the result of the comparison. Options include switching between the two colors, fading, blinking, or flashing (fast blinking). The fade, blink, and flash actions have variants that are active on only true, only false, or both comparison results. If multiple actions are active, the priority byte is used to select which one takes precedence.



Fig. 15. Packaged content tags enable simple applications without requiring additional software. Left, an augmented picture book changes ambient lighting to reflect the story (on this page, red for a desert). Right, a milk carton uses a packed content RFID tag to trigger ambient lighting effects when past its expiration date.

4.3.1 *Ambient Lighting for Storytelling.* In this example, Figure 15 Left, a user reads a picture book whose pages have RFID tags embedded inside them. The tags are positioned so that those not corresponding to the current page are blocked by foil on adjacent pages. The tags contain lighting instructions that match the scenes in the book. For example, the desert scene in our example contains a tag with the EPC 2B 0100000000 88 03 0000 f800, indicating the comparison “tag present”, action “fade 1”, and color red. When the page is turned to the desert scene, the foil in the facing page uncovers the tag, the overhead bulb reads it, and the packaged content interpretation routine in the bulb control software causes the light color to fade to red.

The book also contains a touch-sensitive tag (a tag that can only be read when touched) to allow the user to trigger “lightning flashes” at an appropriate point in the story. The tag’s EPC, 2B 0100000000 ff 09 0000 ffff, indicates to the packaged content routine that the bulb should flash white when the tag is present. The priority field in the EPC is set to ff so that the flash overrides the default colored lighting packaged content tag on the page.

4.3.2 *Food Safety.* Most food items are assigned an expiration date when initially packaged. Food items augmented with RFID tags can encode this expiration date in a packaged-content EPC with the “time” comparison mode. In our example case, Figure 15 Right, a milk carton contains a tag with the EPC 2B 02tttttttt 88 04 f800 07e0, where ‘tttttttt’ is the expiration date. When the tag is read by a nearby light bulb, i.e. when the milk carton is removed from the fridge, the pre-packaged content interpretation routine sees the 2B header, and interprets the rest of the EPC based on the content rules in Figure 15 – in this case, as a time comparison whose result is shown as a red or green blink. From the user’s perspective, the light simply blinks either green or red, depending on whether the expiration date is still in the future or has passed.

header	comparison	pri	act	color 0	color 1
2B	CC CC CC CC CC	PP	AA	XX XX	YY YY

comparison	meaning
00 00 00 00 00	always false
01 00 00 00 00	tag present
02 TT TT TT TT	time > T
fe AA AA 00 VV	byte[A] > V
ff AA AA VV VV	word[A] > V

action	meaning
00	switch
01/02/03	fade (both/0/1)
04/05/06	blink (both/0/1)
07/08/09	flash (both/0/1)

Fig. 14. Our packaged data tags contain a comparison and action within their 96-bit EPC, allowing simple light bulb interactions without special-purpose software.

Similar tags could be used on any food item with an expiration date. However, since the tag will cause any light bulb that can read it to blink, one should use touch-activated tags for items that aren't stored in an RF-opaque location like a refrigerator.

5 DISCUSSION

The design of our RFID light bulb is a fully functional, self contained prototype. However, there are several directions that could be taken in future design iterations. We discuss some of these below.

5.1 Cost

The bill of materials cost of our RFID light bulb prototype is about \$300, which is dominated by the cost of the integrated RFID reader used in our design (~\$200). Future versions of the lightbulb could take advantage of more aggressive hardware integration that combines the processing and RFID reader components [27] to further optimize costs. However, we note that the goal of this work is not to reduce the cost of an RFID reader to that of a light bulb, but instead to make the installation of an RFID reader as simple as screwing in a light bulb. We expect the RFID light bulb to have a lifetime equivalent to that of a normal LED bulb, which is around 20 years.

5.2 Thermal Management

One of the biggest challenges in our current prototype is the dissipation of heat. A primary contributor to the thermal envelope of the light bulb are the RGB LEDs and drivers. While an alternative heat sink design for the lighting hardware could ameliorate this issue, LEDs themselves are becoming more efficient. Much like Moore's law in electronics, Haitz's law [28] predicts that every 10 years, the amount of light produced by an LED will increase by a factor of 20. This would allow an RFID light bulb to easily meet our goal of 650 lumens at much lower power consumption.

The other primary contributor to the thermal envelope of the light bulb is the RFID reader. When operating at a transmit power level of 1 watt, sufficient heat is generated such that it must be duty cycled. Again, thermal dissipation could be improved by an improved heat sink design – the current prototype uses a PCB ground plane as a heat sink. Even with the current design, an adaptive duty cycling algorithm that increases duty cycle during periods of tag activity could greatly reduce the heat generated.

To reduce overall heat density and allow for better thermal dissipation, we can consider additional light bulb form factors. Florescent lighting units are larger and provide additional space to accommodate larger heat sinks. Pendant lighting units would better separate the heat generated by the LEDs and the RFID reader. Both of these alternatives have the added benefit of opportunities for the integration of larger RFID antennas that would provide greater tag read range.

5.3 Alternatives to Wi-Fi

While our current design uses Wi-Fi to connect a network of light bulbs to home infrastructure, there are alternative communication technologies that are also suitable for bridging RFID light bulbs to other infrastructure. A natural fit for a deployment of RFID lightbulbs is Power line networking [13]; AC power is already routed to each bulb in the network and could provide more ubiquitous coverage for large homes that may have only one Wi-Fi access point.

Another interesting direction could be providing a Li-Fi [14] communication downlink, since RFID light bulbs can modulate their RGB LEDs to encode data. Light naturally respects opaque physical barriers and communications would be confined to the room containing the bulb and other devices. This approach could provide automatic location context for receiving devices under the light bulb and provide a more secure way to transmit RFID read events rather than streaming over an RF-based wireless network. The LEDs used in the

current prototype may not switch fast enough to provide a suitable data rate; we leave a Li-Fi optimized LED design as future work.

6 CONCLUSION

In this paper, we introduced an RFID reader in the form factor of a light bulb. This reader can be installed wherever indoor lighting is present. As we have shown with our sample applications, this building-scale RFID-reader infrastructure allows new monitoring, navigation, and interaction applications, as well as supporting existing interactive RFID techniques.

Though our RFID bulbs are useful in their current form, we see several interesting directions that one might wish to tackle in future iterations. Currently, the bulb is limited in RFID read rate and brightness by thermal characteristics of the enclosure; moving to a metal enclosure with a different venting setup would likely cause the bulb to run cooler, allowing for brighter operation and faster reads. In addition, the Intel Edison is a far more powerful CPU than needed for this application. It might, therefore, make sense to change to a simpler processor with lower power requirements, or to use the available surplus computation to run on-bulb tag state estimation. Finally, our prototype bulbs are preconfigured to connect to a Wi-Fi access point with a known SSID, as might be provided by an additional “bulb control hub.” However, it may make sense to allow the bulbs to provide their own ad-hoc wireless network.

We believe that the wide range of wireless, battery-free interactive applications enabled by UHF RFID make it a natural protocol for integration with existing Internet-of-Things deployments, and that our light bulb demonstrates a compelling way to perform such an integration.

ACKNOWLEDGEMENTS

We thank John Mars and Eric Brockmeyer for the light bulb mechanical design, Matt Chabalko for contributing to the antenna tuning strategy used, Mohsen Shahmohammadi for the LED driver hardware design, and Kyna McIntosh for providing figure art.

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Received February 2017; revised April 2017; accepted May 2017