BitID: Easily Add Battery-Free Wireless Sensors to Everyday Objects

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Abstract—Radio-Frequency Identification (RFID) systems are becoming increasingly used within smart environments. In this paper, we propose BitID, a passive Ultra-High Frequency (UHF) RFID based sensing technique that can easily be made using off-the-shelf tags. BitID can be added to everyday objects to enable sensing and control capabilities. With a simple shorting mechanism, BitID is able to differentiate between two states of the object to which it is attached (for example, whether a door is open or closed). We explain the working principle of BitID, and demonstrate how to build and apply it to target objects. We also show that by using a three-layered system architecture, BitID can be used for various applications, including event detection, energy monitoring, fitness tracking, human behavior tracking and control.

Keywords—RFID; Battery-free; Wireless; Sensors; Controller; Smart-Space; Event tracking

I. Introduction

Much effort has been made to deploy sensing techniques that enable monitoring and controlling capabilities in smart spaces. Many solutions are expensive and require a battery to operate. The high cost and maintenance make them unsuitable for ubiquitous deployment. Sensing techniques based on passive UHF RFID technology have been gaining traction in recent years [1]. Passive UHF RFID tags are cheap ($0.07-$0.10) and lightweight. They are available in the form of a sticker with a printed antenna and an integrated circuit (IC). Passive RFID tags are wireless, battery-free, nonintrusive, and inexpensive, making them great candidates for use in ubiquitous sensing systems. However, most proposed RFID tag based sensors require heavy customization of the tag [2]–[5], which increases their cost and size.

In this paper, we present BitID, which is a UHF RFID tag based sensing technique using off-the-shelf tags with minor modifications. The modification adds a simple circuit around the IC and is applied to an object in such a way that the IC is shorted in one state but not in the other. This allows BitID to be used to differentiate between two states of an object (e.g. whether a door is open or closed) based on the inability to be detected by an RFID reader if the short circuit is enabled. Multiple BitIDs may be used in combination to provide multi-state detection for an object (two BitIDs can detect four states of an object). We can use object states and the sequence of their changes to infer about events and human behaviors. Duration of each state can also be calculated for time related applications.

BitID is a low-cost solution compared to specially designed RFID tag based sensors. The ease and flexibility of adding BitIDs to everyday objects enables a wide range of possible applications. The direct change of tag antenna impedance matching makes BitID more robust than other RFID-based sensors used for similar purposes [6], [7].

Our contributions are three-fold. First, we show an easy and robust way to turn off-the-shelf passive UHF RFID tags into sensors. Second, we develop a system to use BitID for monitoring and controlling purposes within a smart space. Third, we demonstrate that rich information can be extracted from BitIDs in a wide range of applications.

II. Related Work

The exploration of RFID for sensing and control purposes in a smart environment has been an ongoing effort. The inexpensive nature of the tags and the ability to be battery-free are the primary attractions. RFID has previously been used to detect human activities [8], [9], monitor objects [7], [10], [11], and enable interactions [3], [6].

Some have combined RFID with other sensors to monitor daily behaviors. The Wireless Identification Sensing Platform (WISP) [12] harvests energy from the RFID reader to supply on-chip microcontrollers and sensors such as temperature sensor and accelerometer [2], [13]. More information can be gathered with added sensors, but it requires customized hardware, which increases cost. It's also rigid and thicker than off-the-shelf RFID tags, making it unsuitable for certain applications.

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Bhattacharyya et al. proposed an antenna structure mixed with specially designed circuits to turn the RFID tag into a sensor [4]. It decodes the impedance mismatch caused by the antenna structure change, and uses the degree of mismatch to sense temperature [14] or displacement [15]. However, special temperature sensitive materials must be used in this technique.

Selker integrated a switch into an RFID tag in order to attach and detach the IC chip. This allows the RFID card/tag to be manually enabled and disabled [16]. Hemmert et al. took a similar approach, and explored the possible interactions if the tag is placed on the back of a phone [17]. Buthe et al. implemented tilt switches on the RFID antenna structure, enabling an electronically read, passive die [18]. Marquardt et al. showed how to enable interactive RFID tags by adding low-power electronics to the tag [19]. However, these all require heavily customized RFID tags, which can dramatically increase cost and/or complexity compared to using off-the-shelf RFID tags.

Li et al. explored detection of human interaction using off-the-shelf RFID tags for detection of dynamic behaviors when there is relative movement between tags [6]. In PaperID [3], Li et al. detected human tag interaction events by analyzing low level RF channel parameters. However, their method is vulnerable to electromagnetic disturbances such as people walking around the tag. Heavy signal processing is also required.

III. Method and Implementation

In this section, we first explain how the RFID system works, then we present the design and building process of BitID. We also demonstrate how to deploy BitID to objects. Lastly, we show the system framework and our implementation of BitID within a smart environment.

A. RFID system principle

An RFID system usually contains a host processing unit, a RFID reader, one or more antennas, and RFID tags. The host unit is used for system control and data display. The reader consists of one central processing unit and one or more antennas. An RFID system is shown in Fig. 1.

The reader sends out interrogating signal through its antennas. The signal induces alternating currents on the tag antenna, which is used to power up the integrated chip. When powered up, the chip modulates backscattered waves to send information to the reader. The modulation is done by switching its input impedance between a matching state and a non-matching state (a direct short in most cases [4]), according to the data stored in its ROM. Changes of input impedance of the chip will change the reflection coefficient ($\Gamma_{1,2}$) accordingly, which leads to different current distribution on the tag. The amplitude and/or phase of the backscattered signal are then changed, enabling amplitude and/or phase shift keying (ASK and/or PSK) modulation. The differential radar cross section (RCS) $\Delta\sigma$ for the tag is used to describe the modulation of a tag [20]

$$\Delta\sigma = \frac{\lambda^2 G^2}{4\pi} \left| \Gamma_1 - \Gamma_2 \right|^2$$

In which λ is the wavelength of interrogating signal, and G is the directivity pattern of tag antenna. The reader then demodulates the backscattered signal accordingly. The larger the differential RCS, the cleaner the modulation will be, leading to easier tag detection by the reader. The reader then sends the host report of detected tags with IDs, timestamps, low-level RF channel parameters, etc.

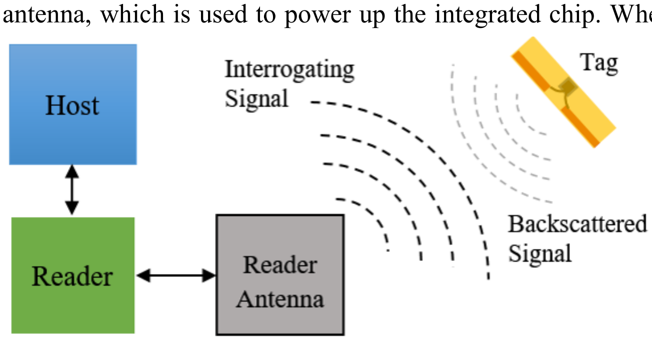

Fig. 1. Working principle of a RFID sytem

B. Design and prototyping

We designed BitID to be undetectable by an RFID reader when it is in a certain state. We achieve this by disrupting tag modulation in one state, and restoring the modulation in the other state. Based on the analysis in the previous subsection, a close to zero $\Delta\sigma$ would make the tag invisible to the reader.

Our method controls the value of $\Delta\sigma$ by shorting around the chip in one state, but not in the other. When shorted, the chip is always in a non-matching state ($\Gamma_1 \approx \Gamma_2$), which minimizes $\Delta\sigma$ and makes the tag absent from reader detection. When the chip is not shorted, the reader is able to detect the tag per usual operation. To short around the chip, we expose antenna structure on both sides of the chip, and apply two conductive strips to those areas. The chip can then be shorted when the two strips are electrically connected together. The process to modify a tag is shown in Fig. 2.

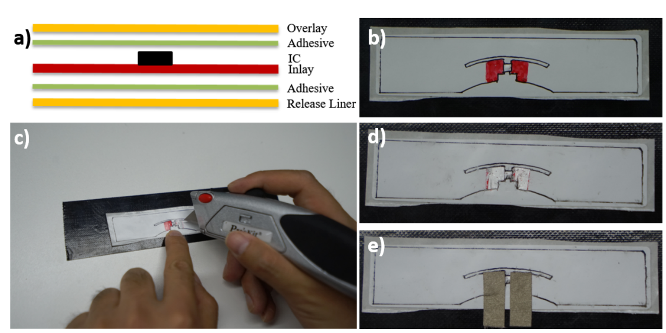

Fig. 2. Process to build a BitID tag. (a) ALN-9654 inlay stackup; (b) Mark the area around chip in red; (c) Use knife to carefully remove the marked area; (d) RFID tag with overlay removed; (e) Attach conductive tape to create strips that may be shorted together

We use UHF RFID tags for their wide accessibility and small form factor. An ALN-9654 [21] white wet inlay fit our purpose adequately due to its large connection area around the chip. Its structure is shown in Fig. 2(a). The antenna is printed on the inlay. The building process is shown in Fig. 2(b-e). The outline of the tag is sketched for a clear view, and the area to be peeled off is painted in red. After carefully removing the overlay of the marked areas, we attached conductive tape to create shorting strips. The two strips can then be shorted using a conductive material to connect the strips together.

C. Verification by simulation

We conducted an electromagnetic simulation to verify and study tag operation when shorted around the chip. We used CST Studio 2015 to simulate an RFID tag matching and non-matching state. Based on the reciprocity principle of electromagnetics, the currents induced by a port in the position of the IC chip should be the same as those induced by the far-field interrogating signal. By switching the port impedance between $Z_1 = 11.19 - j121.91$ (matching) and $Z_2 = 0.01$ (non-matching), we can simulate the surface current of the tag in the two states respectively. Results are shown in Fig. 3. When the tag is not shorted as shown in Fig. 3(a-b), the current strength is very different under two states, meaning a clean modulation. When the strips are shorted as shown in Fig. 3(c-d), current strength is similar under two states, meaning the modulation is impaired and thus difficult for the reader to detect the tag. If the strips are too long as shown in Fig. 3(d-f), however, larger currents will flow around the strips in a matching state. This may cause the tag to become detectable if the interrogating signal strength is high enough. Keeping the strip length as short as possible is the safest way to mitigate this concern.

D. Deployment

Two parts are needed to deploy BitID to a target object: the modified tag, and a conductive material that can short the two strips together. The conductive material used to short the strips could be conductive tape or a metal contact surface on the object directly. The BitID should be applied to the object such that the two strips are shorted by making contact with the conductive material in one state of the object, but disconnects from each other in the other state. The applicable target objects should have relative movement when switching between states. In most cases, part of the object remains static in different states, while part of it moves between states. For example, a window moves away from its frame when opened, and makes contact with the frame when closed. We can put tags on the window frame and the conductive material on the window in such a way that they will only make contact when window is closed. Then we know the window is open when the tag is detected by the reader, and closed when it's not. We suggest applying tags on the non-moving part for a more consistent reading by RFID reader. Depending on specific objects, the exact applying procedure may vary. We show several examples in Section IV.

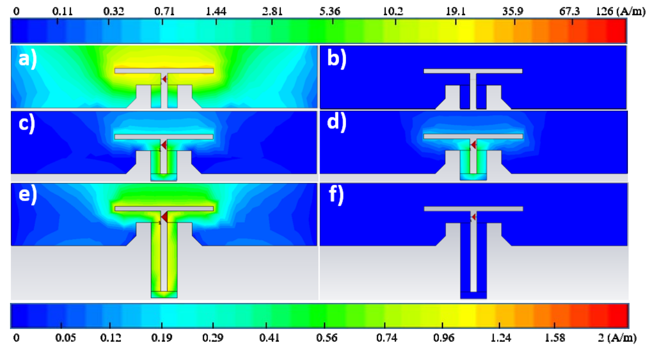

Fig. 3. Surface current on a tag. (a) and (b) on the top scale, (c)-(f) on the bottom scale. (a) Tag with strips (matching state); (b) Tag with strips (non-matching state); (c) Tag with shorted strips (maching state); (d) Tag with shorted strips (non-maching state); (e) Tag with long shorted strips (maching state); (f) Tag with long shorted strips (non-maching state).

E. System and implementation

In this work, we used Impinj Speedway R420 UHF RFID readers and standard antennas. Low Level Reader Protocol (LLRP) is used by host to communicate with the reader. Information including Tag ID, RSSI and Phase is reported through Ethernet. We collect all these data and employ a three-layer system framework as shown in Fig. 4.

Digital Binary Layer. Once the BitID is attached to an object, the state of the object is digitalized. We define a True/False state of each BitID based on whether or not it is detected by the reader. A timer with a certain period is used for checking the states of each BitID. This turns BitID into a sensor with one bit of information. Multiple BitIDs can easily be used in combination to enable multi-bit sensing. Each BitID tag is distinguishable using the identification feature of RFID. These BitID tags constitute the digital binary layer.

Semantic Layer. BitID consists of four semantic features, which are *state*, *event*, *behavior,* and *duration*. *State* infers the states of objects at a specific time. *Event* indicates the state changes of the object. *Behavior* consists of an array of *state* recordings over a period of time. *Duration* indicates both how

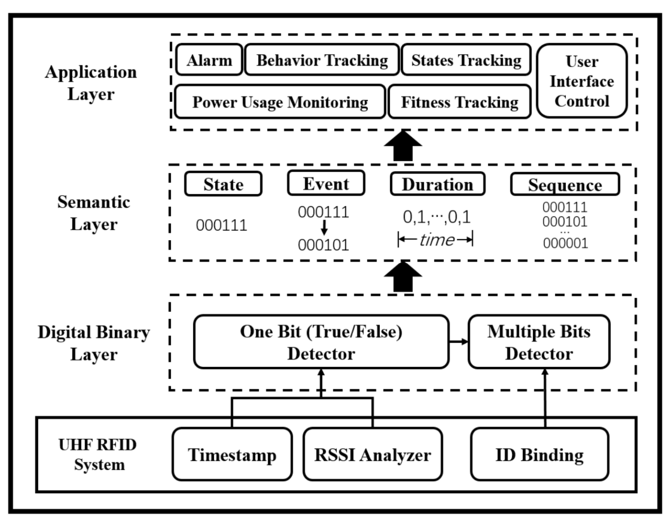

Fig. 4. System framework

long the object stays in one specific state and frequency of state changing.

Application Layer. Combining the features in the Sematic layer, the system can support a number of applications. Several categories are listed in Fig. 4. We present some application use cases in the next section.

IV. Application Scenarios

In this section, we show various applications to demonstrate the proposed methods for monitoring and/or control of events. We first show that BitID can be used to monitor binary state changes of objects. We then show that by recording timestamps of each state change, BitID can be used for energy monitoring and fitness tracking purposes. We also show multiple BitIDs together can be used to infer more information, such as human behaviors. Lastly, we show that BitID can be utilized for adding control functionality to everyday objects and video games. This section is organized into five sections:

A. Security/Safety

By attaching the BitID to doors and windows, we were able to create a home security demonstration system to detect, record, and notify about entry. Using BitID allowed us to apply door and window sensors without the need for hard wiring or powered sensors. In Fig. 5. image a) and b), the door outfitted with BitID is shown in an open and closed position, respectively. In image c) and d), the window outfitted with BitID is shown in an open and closed position, respectively. By integrating this system with an Android App, we were able to view real time state monitoring of doors and windows and access past usage logs. Push notifications could also be added to notify about security related events while away.

B. Energy Monitoring

1) Monitoring Water Usage of a Drinking Tap

BitID can be used to monitor water usage. In Fig. 6, a BitID tag is applied to our filtered drinking water tap. Image a) is in the off position and Image b) is in the on position. Image c) is a graph showing the water faucet being turned off/on several times in a row. This tap is controlled by a pump, is either on or off, and flows at a known constant rate. This allows for cumulative tracking of water usage along with time stamps of when the water was used. Besides tracking the water usage and drinking habits of the users, this data may be used to determine when to replace the filter. In the future, a system like this could notify you that it is time to order a new filter or even order the new filter for you automatically when it is time.

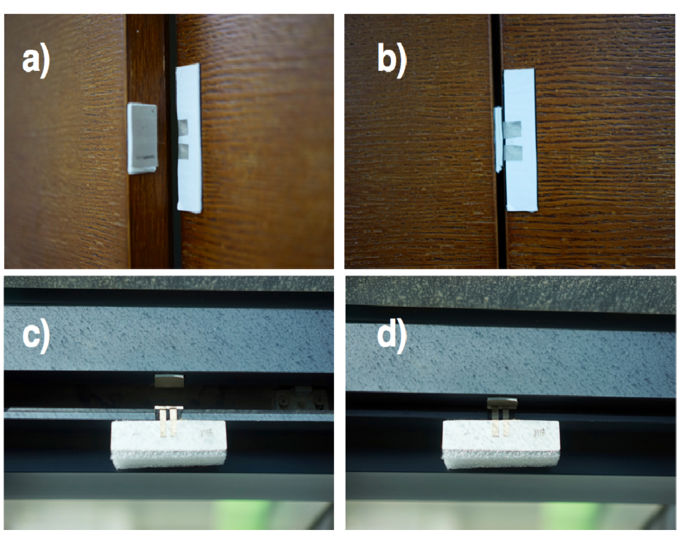

Fig. 5. BitID is applied to a door and a window: (a) opened state of door, (b) closed state of door, (c) open state of window, (d) closed state of window

2) Electrical Usage of Lights in a Conference Room

To measure the energy usage of our conference room lights, we applied the BitID to the light switch by the method shown in Fig. 7(3a-3b). As can be seen in Table I, we obtain usage times of the conference room based on the lights being on or off. Our conference room lighting is comprised of eight T5 28W bulbs. Using duration, we are able to calculate energy consumption of the lighting.

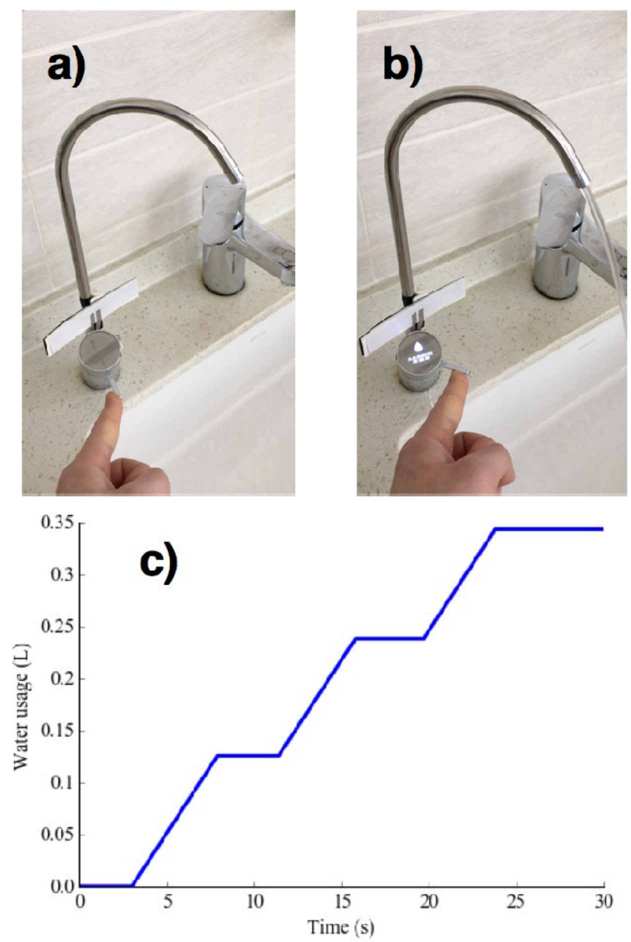

Fig. 6. BitID is used to monitor water usage on a drinking tap: (a) shows the off position, (b) shows the on position, and (c) shows a graph of water usage over time.

TABLE I. LIGHT ENERGY CONSUMPTION IN MEETING ROOM

Time	Duration (mins)	Energy Usage (Wh)
09:03-10:19	76	283.7
10:43-12:03	80	298.6
18:00-19:20	81	302.4
19:50-20:21	30	112.0
Total	267	996.7

C. Behavior Tracking

Much of the early work in using objects to obtain usage context relied on computer augmentation of the objects in order to add them to a communications network [22]. Later studies, which benefited from commercially available sensing devices added to objects, showed that human behavior can be gathered through monitoring interaction with objects [23]. With the deployment of pervasive sensors within an environment, it has been shown that machine learning can be used to recognize behaviors and optimize environments within a smart space accordingly [24], [25]. RFID has also been explored for tracking interaction with objects directly by adding an RFID reader to gloves worn by a user and tags to items [26]. These previous techniques used powered components on the objects or on a wearable device, which increases costs, complexity, and maintenance of the system. For BitID, however, a modified passive tag is simply added to the objects within an RFID smart environment. To explore this approach, we applied our tags to a coffee maker, door, light switch, medicine container, coffee mug, and a chair contained within a smart environment as shown in Fig. 7.

In Fig. 8, a behavior sequence using our BitID environment shows a subject entering the space triggering the door sensor, followed immediately by turning on the lights. Then, based on the amount of time between the lights turning on and the chair sensor activating, we can ascertain that the subject walked directly to the chair and sat down. The subject then interacts with their medicine container followed by an interaction with a cup, which shows taking a drink to swallow

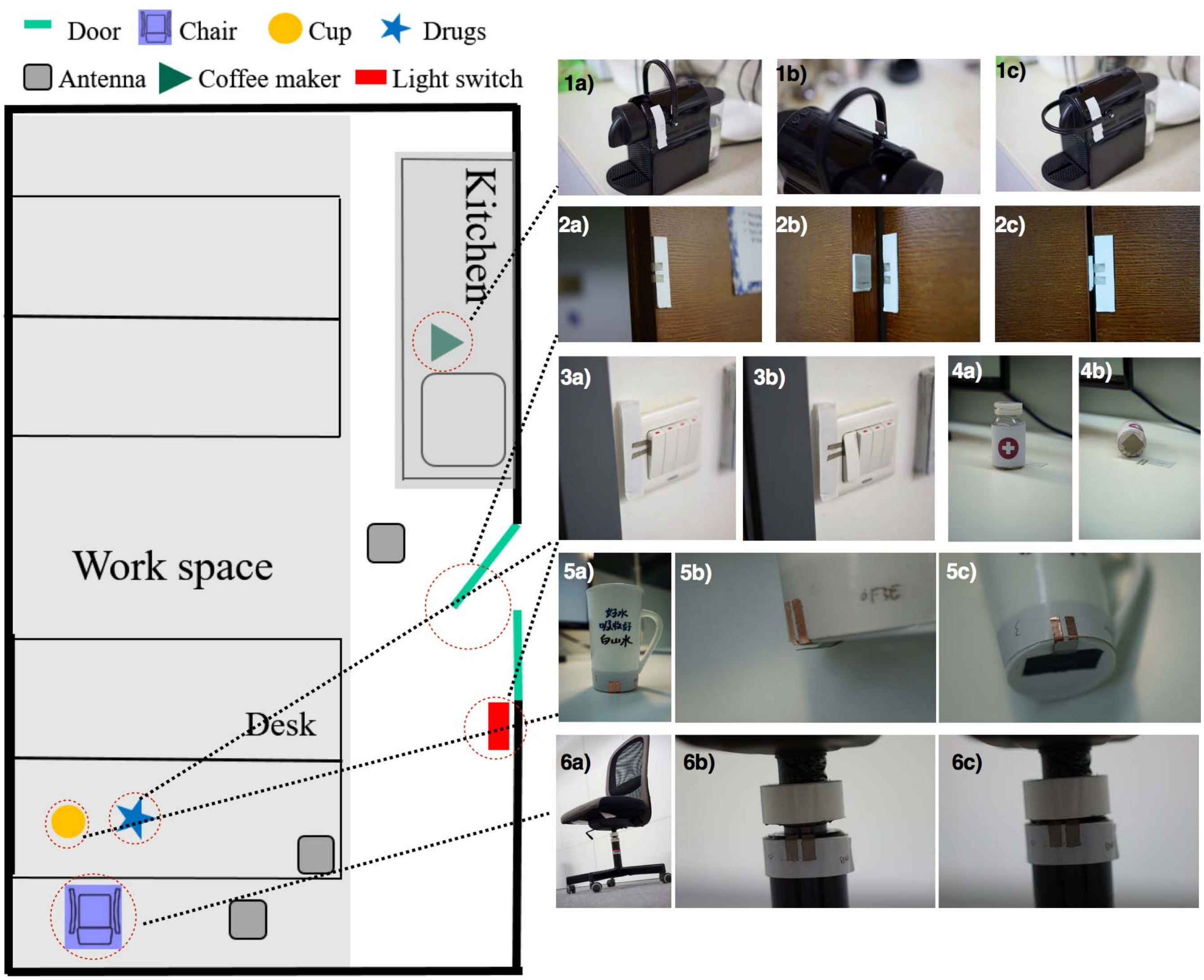

Fig. 7. BitIDs are applied to objects within an RFID smart environment. The left side shows the room schematic and object location. The right side shows BitIDs applied to a coffee maker (1a-c), door (2a-c), light switch (3a-b), medicine container (4a-b), coffee mug (5a-c), and a chair (6a-c)

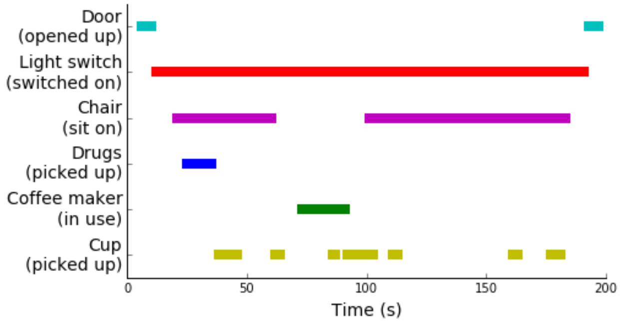

Fig. 8. A behavior sequence executed in the RFID smart-environment shown in Fig. 7.

pills. The subject then gets up from the chair while also handling the cup. Soon after, the coffee maker is engaged and the subject returns to sitting in the chair. During the remaining period the subject continued to interact with the cup by drinking coffee while seated in the chair at the desk. The sequence is ended when the user gets up from the chair, turns off the light, and uses the door to exit. This example is a snapshot of the type of data and patterns that can be collected to inform about behavior.

D. Fitness Tracking

The use of a passive sensor for fitness tracking is advantageous, as it does not require the user to wear any sensors and it also does not require a power source on the fitness equipment. To demonstrate this, we added a BitID to an exercise bike as shown in Fig. 9(a-b). The bike we used is a fixed gear spin bike and the number of rotations of the crankshaft is directly proportional to the rotation of the wheel. We used this setup to measure the real-time speed of the user and from that we calculated distance, which is shown in Fig. 9(c).

E. Controller

1) Video Game controller

In recent years, the video game industry has moved to wireless remote controllers. For example, PlayStation 4 controllers use Bluetooth 3.0 for wireless communication. As a result, video game controllers contain batteries and must be recharged. A Battery-free wireless Joystick game controller has been explored using RFID backscatter to power an on board accelerometer [27]. Here, we demonstrate a simple method to create the game controller buttons using BitID. Our battery-free wireless game control button is pictured in Fig. 10(b-c). The RFID is placed in a 3D printed case and a click button is used to short the chip. We used BitID to trigger a click event on the PC in order to play Flappy Bird. This same method could be applied in the future to create more dynamic game controllers or other devices such as wireless computer keyboards that do not require a battery.

2) Light control

Similar to the BitID video game controller, we applied a BitID button to the side of a coffee mug as shown in Fig. 11(a-c). This placement allowed us to demonstrate the use of the button on an everyday object. In this application, we used the button to control lighting. The first tap turned the light on and subsequent taps increased the intensity of the light before reaching the off position again. Sequentially, there were five

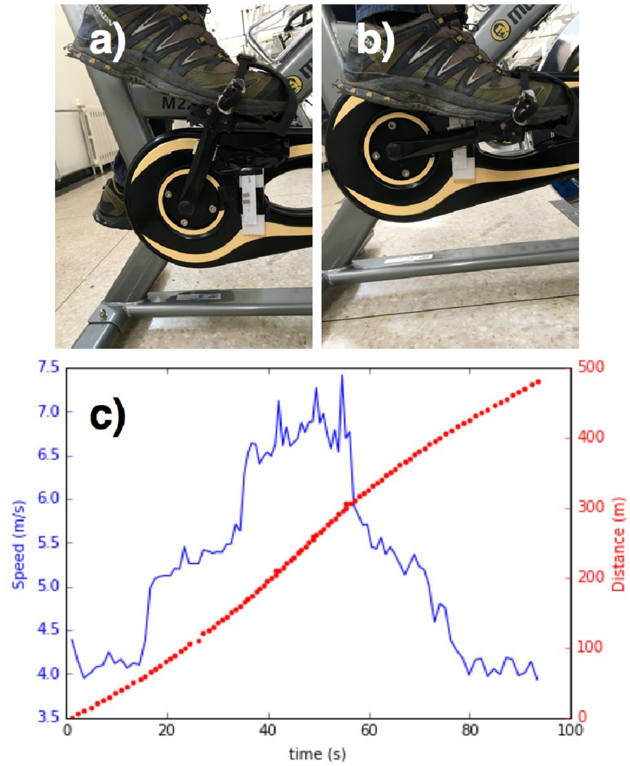

Fig. 9. BitID is added to an exercise bicycle: (a) shows the BitID in a detectable position, (b) shows BitID in the shorted position, and (c) shows a graph of the bicycle speed and distance over time.

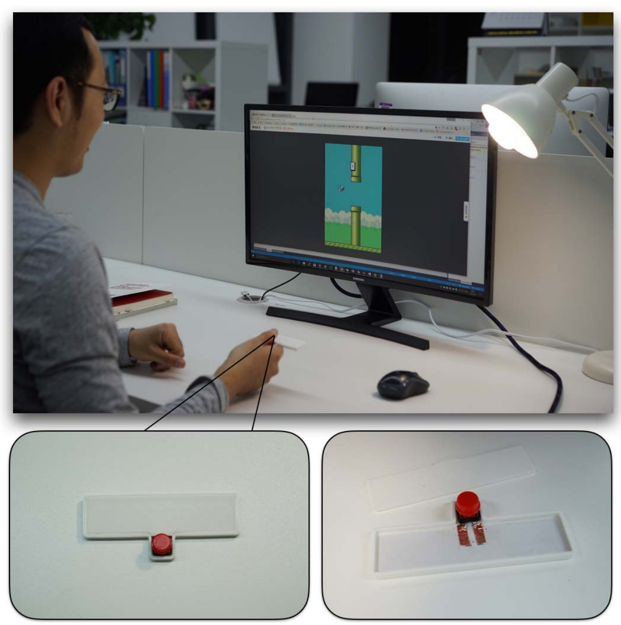

Fig. 10. BitID is used as a video game controller: (a) shows BitID being used to control Flappy Bird, (b) and (c) shows details of the controller.

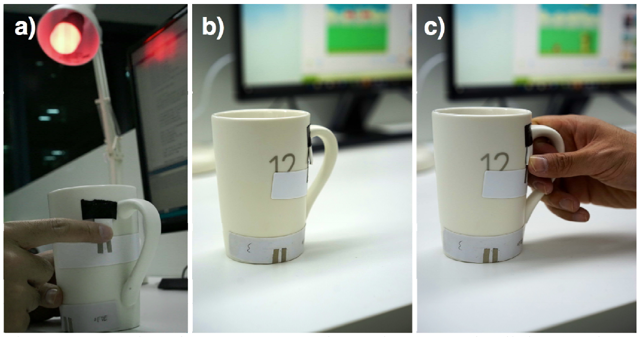

Fig. 11. A BitID button on a cup is used to control a light: (a) shows the interaction with a smart bulb, and (b) shows the BitID in a detectable state, (c) shows BitID in a shorted state by pressing the button.

states; off and four levels of brightness. This same method could be used to add very cheap buttons to everyday objects in order to do things ranging from room and appliance control to ordering replacement consumables. This button could even be printed directly into packaging of goods, such as laundry detergent, for reordering purposes. A battery-free wireless programmable button is a very extensible platform to add digital functionality to everyday objects.

V. Discussion

In this paper we explored using RFID tags for monitoring events in a smart environment as well as their use as simple push button controllers. In addition to our method of creating a physical short around the chip, other methods such as disconnecting and reconnecting the chip could also be used. There may be method preference based on the chosen application. Using the security application as an example, a signal could be jammed allowing the door to be opened without detection of the tag. This would be viewed as the door still being closed, which would be a clear security concern. Using the disconnect method for the door instead would reverse the state signals and might mitigate concerns of jamming. More study is needed to explore the benefits or downsides to each method.

Comparing to behavior and state monitoring methods that rely solely on low-level RF parameters, our method may have better performance in an electromagnetically chaotic environment. While the RF parameters can be heavily distorted by electromagnetic disturbance, our method works as long as the reader can read the tag when it's on (not shorted). To deal with possible misdetections, we plan to add algorithms to filter out detection errors based on on-off time interval, or low-level RF parameters like RSSI and phase information when the tag is on.

One of the limitations of BitID is due to the limitation of placement of RFID tags directly on metal surfaces, which results in RFID antenna impedance mismatch. We were able to overcome this obstacle in our window application shown in Fig. 5(c-d) by putting foam between the metal surface and the tag to act as a spacer. This may not be a suitable solution for some applications and is thus a limitation of this method. BitID is also limited to mechanical interactions. For example, it cannot be used to detect if the TV is on. There are also limitations of range and cost. For UHF RFID tags, the typical maximum range is 3-5 meters. Several RFID readers and antennas are then needed to provide adequate coverage area, which increases system cost. But with the decreasing cost of electronics and improving antenna performance, this issue may be mitigated in the future.

Even though BitID can be used to detect multiple states, we only show binary state detection applications in this paper. The reason is that we find binary state detection is enough for most everyday applications. For example, we want to know if a door is open or closed, but often times are not interested in how open the door is. We also plan to explore a method that enables one BitID to detect more than two states. If this could be realized, it would open BitID to more applications.

VI. Conclusion

The ability to inexpensively add battery-free wireless sensors to everyday objects will greatly ease the realization of ubiquitous computing systems. In this paper, we explored modifying RFID tags to use as simple smart-environment sensors and controllers. We designed and verified the shorting mechanism for BitID, and showed in detail how to apply BitID to everyday objects. We then explained how to use BitID to detect object events and infer human behaviors. We applied this to applications in security/safety, energy monitoring, fitness tracking, and behavior tracking. We also used the method to create battery-free wireless controllers. We built a video game controller (flappy bird as our demo) and a smart light controller (coffee mug button demo). RFID sensor networks show much promise for use in smart-environments, and with decreasing costs and increasing range, RFID will become even more promising in the future.

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