Home Automation and Personalization Through Individual Location Determination

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ABSTRACT - The focus of this project is to develop a prototype to demonstrate the utility of individualized location determination for home automation. While current home automation systems provide localization at a GPS level, they do not identify users' locations within a building. The smart home technology market is growing rapidly and this feature can differentiate a product line by adding unique capabilities for the consumer.

The objective for this system is to use individualized location determination to improve lifestyle areas in the home in passive and non-intrusive ways. Being passive is important in that users should not have to take extra steps (e.g., pushing a button when they enter a room) as they move throughout their house. Being non-intrusive is important because users should not have to wear anything extra (e.g., a special armband) or have personal information scanned (e.g., facial recognition camera).

The system will use Bluetooth Low Energy (BLE) to identify and track users' movements throughout a house, where the BLE signal of an individual will be associated with a smartphone or fitness wearable that they normally carry with them. A unique aspect of this project is the implementation of a flipped BLE architecture, which is implemented with a Texas Instruments development board that acts as a beacon to identify users based on their BLE signals from their smartphones and wearables. This architecture is "flipped" because most BLE beacons rely on a smartphone to "see" the beacons whereas the beacons in this system are "seeing" the smartphones. After identifying BLE devices in proximity to the beacon, the prototype system will record readings on the beacon locally, store data in an SQL database, and clean and process data through a PHP script. Different use cases for the BLE system within a house were considered. The final prototype will focus on a Smart Thermostat application which automatically adjusts where a thermostat reads the indoor temperature based on the location of the users.

Results include a fully functioning prototype that can be used to demonstrate feasibility of the home automation use cases. Test results from the prototype include using a factorial experiment to measure the effect of distance and obstacles on the signal strength readings as well as performance on the system through a range of scenarios.

Index Terms –Bluetooth Low Energy, Bluetooth beacons, home automation

INTRODUCTION

Devices like smartphones and wearables are becoming more prevalent and integrated in everyday life. This has created a growing market for home automation systems. Companies selling home security systems are in an advantageous position to capitalize on this trend because their systems are already installed in homes. Current home automation systems can locate a user via their devices, such as smartphones and fitness wearables, to perform functions like locking the house doors while a user is at work or adjusting the thermostat setpoint when a user is commuting home. These systems, however, use GPS data which limits the accuracy of the location determination to the house-level. A home automation system that can locate users to room-level accuracy will increase the potential applications and functions of the system. This system must be non-intrusive to the users' lives, accurate in detection, low-power consumption, and easily integratable with their current home security system.

The overall objective described in this paper is to create a functioning proof of concept prototype that can determine the location of someone in their home on a room-by-room basis. This research concluded that using BLE beacons with the smart devices is a viable means to achieve this goal while also being non-intrusive for users.

LITERATURE REVIEW

The Internet of Things (IoT) is a rapidly expanding industry that is continuing to grow. In fact, "every day 5.5 million new things get connected to the Internet of Things" and it is projected that by 2020 there will be 30 billion connected devices, a huge increase from the current 6.4 billion devices [1]. Smart home technology falls within this field. While the idea of a smart home is not a new one, the growing IoT space and emerging technologies are making new applications possible.

I. Alternatives Considered

To meet the criteria for an accurate, passive, non-intrusive system with a long battery life, multiple options were considered. The main options for location devices were RFID, facial recognition, and smartphones. Both RFID and facial recognition software were ruled out because they do not meet the non-intrusive objective. RFID requires the user to wear an additional piece of technology and facial recognition

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software is invasive to the user's privacy [2]. There are currently projected 4.77 billion smartphones in use today [3]. The use of smartphones is so widespread now that seventy-nine percent of people ages 18-44 have their smartphones with them 22 hours a day [4]. This supports the viability of using the smartphone as a non-intrusive method to locate a person within their home.

In addition to a location device, a wireless personal area network (WPAN) is a central part of an indoor location system. There are many choices available when trying to select the best WPAN such as ZigBee, traditional Bluetooth, and Wi-Fi. Bluetooth Low Energy stands out for a variety of reasons. ZigBee is not found in iPhones and therefore is not conducive to smartphone localization [5]. Wi-Fi is designed for computer-to-computer, communication and consumes a large amount of power; so while Wi-Fi is compatible with mobile devices, it is not the best solution [6]. While traditional Bluetooth has all of the functionality to successfully implement this project the standard was designed to transmit large quantities of data, resulting in an excessive power draw unnecessary for this application [6].

Before BLE, every new Bluetooth version increased the data transfer rate and elongated scan time, with an average scan time of approximately 10 seconds. This caused an associated increase in power consumption and limited its value for localization [7]. Heydon argues, "that you cannot achieve high data rates or make low energy work for use cases that require large data transfers or the streaming of data" [8]. However, the new Bluetooth protocol (i.e., Bluetooth Low Energy), supported by modern smart devices, has overcome the limitations of long scan times [7]. This presents a technical challenge since the system must operate on a minimal power budget so that it can "work with button-cell batteries," but be robust enough to transmit adequate data with multiple BLE devices when necessary [9]. Another design factor that was considered is the total cost of the BLE beacons. A bigger battery is more expensive, therefore minimizing energy usage also minimizes the size and cost requirements for the battery supplying power to the device.

With the small size, minimal power consumption, low cost, and wide use in smartphones and fitness wearables, BLE has key attributes of a technology to provide indoor micro-localization. A main priority of the system is to provide additional functionality to users while staying non-intrusive, and by utilizing BLE, users will not have to purchase or wear any additional devices.

USE CASES

Three use cases define areas where within-house location could provide value to the consumer: the smart thermostat, the security sensor for home entry, and the sleep mode.

I. Use Case 1: Smart Thermostat

The smart thermostat use case consists of connected thermostats and additional remote temperature sensors, which are devices offered by several home automation companies.

The temperature sensors are able to record the temperature of the room they are in and communicate that data to the smart thermostat, allowing the thermostat to read the indoor air temperature from any room rather than just from the thermostat. Bluetooth Low Energy is applied to this use case by automating the selection of from which sensor the indoor air temperature is read. The basic principle is to read the temperature from wherever the most people are. This application improves the lifestyle of the user by ensuring that the occupied rooms or areas of the house are kept at the proper temperature. For this use case to be effective, there must be at least one beacon present for each temperature sensor.

II. Use Case 2: Home Entry

The home entry application uses a BLE beacon and a security sensor that are both aimed at the main entryway of the house. When the security sensor detects someone entering the house, it takes a photo and the beacon will search for a BLE advertisement from their smart device. If the person's smart device is registered in the system, the photo is tagged to that user and saved to their personalized image folder online. If the smart device is not recognized or no BLE advertisement is detected, the image is tagged as "unknown person." Administrative users, such as parents or guardians, can choose to receive notifications on their mobile device when a specific user is detected entering the house, such as a child arriving home from school. This improves the user's lifestyle by offering peace of mind knowing who is entering and exiting the home when.

III. Use Case 3: Sleep Mode

The sleep mode application adjusts a set of home automation processes at the same time to specific settings set by the user. For instance, the sleep mode might entail locking doors and windows, turning off lights, and adjusting the temperature when the residents are going to sleep. This can be enhanced with BLE by allowing the mode to activate automatically when certain conditions are met, such as detecting specific users in their bedrooms after a certain time. Currently, a user has to activate a mode via their smartphone application, but incorporating BLE will remove the need for manual input from the user.

IV. Failure Points

Each use case was selected to minimize risks in case of system failure. For instance, using BLE to activate an alarm is not a use case because the system may not operate if someone left their phone at home.

There are five failure modes associated with this system. The system is designed so that these failure points do not prevent the main functions of each use case from working properly. Table 1 maps the consequences of the five failure modes are for each of the use cases. The five failure modes are as follows:

1. If a user does not keep their phone with them at all times inside the house
2. If a user loses their phone
3. If the phone's battery dies
4. If the device's Bluetooth is not turned on
5. If a beacon's battery dies

TABLE I
FAILURE MODE CONSEQUENCES PER USE CASE

Use Case	Failure Mode 1	2	3	4	5
Smart Thermostat Single User	F	D	D	D	D
Smart Thermostat Multi User	F	U	U	U	D
Home Entry	WT	WT	WT	WT	NT
Sleep Mode	NA	NA	NA	AU	AU

The consequences are defined as:

F: Faulty detection, may heat/cool thinking it knows where the user is
D: Default, does not see anyone, uses default sensor
U: Missing user, does not consider where that one user is
WT: Wrong tag "unknown person"
NT: No tag, alerts user that beacon is not working
NA: Not activated, No phone alert
AU1: Alert user that Bluetooth is off and it is their normal bedtime
AU2: Alert user via phone that beacon is not working

The smart thermostat application was determined to be the best use case around which to create a prototype because it requires the most complex data processing and use of BLE. Successful prototyping for this use case can imply feasibility of the other use cases which require simpler processing. The prototyped system will identify users and their locations via their smart devices and send this information to be processed in an online database. This will allow the system to recognize when a room has been occupied for enough time to dedicate that room's temperature sensor as the set point for the system.

TECHNICAL APPROACH

I. System Architecture

Bluetooth Low Energy is normally set up in a master-slave relationship, using the terms Central and Peripheral to describe those roles. The Central device is the main device, such as a smartphone, and there can be multiple Peripherals, such a heart rate monitor or glucose level sensor, for a single Central device [9]. Beacons that are used by commercial stores are one such Peripheral, allowing your phone to see them if you are running the store's app. This project explores a different BLE approach that flips the roles: the smartphone is now akin to the Peripheral and the Beacon is the central device. To achieve this, the flipped architecture puts the smartphones in Broadcaster mode and the microcontroller beacon in Observer mode. While a Central and Peripheral device need to establish a dedicated connection to transfer application specific data like heart rate readings, a Broadcaster and Observer communicate via more generalized packets called advertisements. The Broadcaster smartphone transmits advertising packets containing its Universally Unique Identifier (UUID) for any Observer device, like a microcontroller beacon, to receive and analyze. In this way, an Observer is a Central device that does not initiate connections with the Broadcasters it receives the advertisements from [9].

Operating the beacon in Observer mode is less resource and energy intensive than Central mode because it requires both less transmitting and less receiving. The flipped architecture was adopted for this project because all that is needed for micro-locating devices is the UUID and Received Signal Strength Indicator (RSSI) contained in the advertising packets [10]. The Observer beacons can determine which device is in their vicinity via the UUID and how close it is via the RSSI. The more traditional BLE beacon architecture, on the other hand, would have required smartphones to have a specific app running and would have completely eliminated the possibility of fitness wearables from being used. This would have diminished the usability of the system for home automation micro-location determination.

The two main components of the prototype system are the hardware and the database. The hardware approach involves a BLE beacon collecting UUID data from a smart device and formatting it in preparation for the database component. For the prototype, the hardware transfers data to the database via a wired connection after it has completed collecting data. Once the data is read into the database, it is processed to micro-locate people within the home and update the temperature sensor used based on location and movement.

II. Hardware Approach

The main goal from the hardware portion of the project is to provide a proof of concept Observer beacon that demonstrates the value of using the flipped BLE architecture. This was accomplished using the Texas Instruments (TI) development environment and real-time operating system (RTOS). Many of BLE tasks were made possible by the Application Programming Interfaces (APIs) in the BLE Software Stack made for use on the TI CC2650 microcontroller [9]. To connect the beacon with the rest of the prototype system, it needed to operate in two modes: data collection and data communication. In data collection mode, the beacon collects UUID advertisements from any BLE device within range that are passed to it by the BLE Software Stack and parses out the UUID and RSSI. After cleaning the data, it is stored locally. This process tells the BLE Software Stack to scan for advertisements on an interval timer. In data communication mode, the beacon connects to a computer via a Universal asynchronous receiver/ transmitter (UART) connection and sends the data it has locally stored over the line of communication. The Observer beacon identifies itself along with the data it transmits so the system can know which advertisements were picked up by which beacon if the system contains multiple beacons.

III. Database Approach

The computer on the receiving side of the UART connection processes the incoming raw bytes into a comma-separated values (csv) file with the Beacon ID, UUID, and RSSI formatted. The data inputs of Beacon ID, UUID, and RSSI from the csv are inserted into the SQL database and linked to map the user location to a room, temperature sensor. User and zone information are inputted into the database upon setup. Because the RSSI fluctuates based on external factors, user location is determined by looking at the ten most recent readings and taking the statistical mode [11]. For each device, the beacon with the strongest signal strength is considered to be the location of that device. The temperature sensor in the room with the most people is used to provide indoor air temperature to the thermostat. This sets the temperature sensor based on room population density. To avoid fluctuation of the temperature sensor while a user is moving throughout the rooms, the system waits for a user to remain stationary for 10 minutes before re-evaluating the user location. Additionally, the historic use of rooms and temperature sensors are stored for both information gathering and tampering detection purposes.

The readings are stored in a SQL database and a PHP script interacts with the stored data to implement the actual changes in the temperature sensors and thermostat. The PHP script communicates with the tables of stored data to associate a device with a person, then a person with the room they are currently in, and then the population density of people within each room with the optimal temperature sensor to use.

TESTING AND RESULTS

Testing aimed to determine what factors have the biggest effect on RSSI with the goal of evaluating if the beacon could accurately differentiate between a device in the same room and a device in a different room. Any number of factors could have an impact on RSSI, therefore screening experiments were used first to eliminate factors without significant effects and then followed by a factorial experiment on the remaining factors.

I. Screening Experiments

Screening experiments were used to determine what factors were significant enough to warrant further analysis. Factors tested include:

- Distance between beacon and device (3 ft, 10 ft, 15 ft, 20 ft, 25 ft, and 30 ft)
- Location of the device (in hand, in pocket, and on a table)
- Obstacles between the device and the beacon (none, body, door, and wall)
- Orientation of the device (antenna face out and antenna face in)

These preliminary experiments measured 10 RSSI values in each level of a factor, while keeping the other three constant. This was not to analyze interaction effects but rather to determine what factors should be considered in further testing.

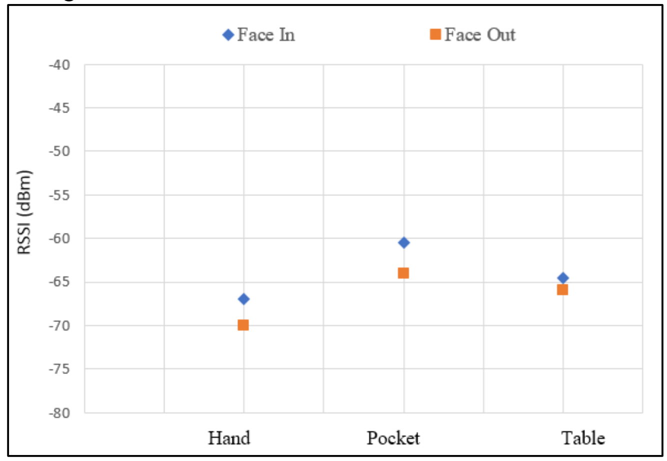

FIGURE 1
EFFECT OF ORIENTATION AND LOCATION ON RSSI

Neither location and orientation showed a meaningful effect, while obstacle and distance both showed substantial effects. Figure 1 shows the mode for RSSI at different locations, antenna face in and face out. This shows no important difference between these factors and RSSI; the difference in modes was no more than 7 dBm, which is small enough that it could not be differentiated from natural variability. Therefore, location and orientation were not included as variables in further experiments.

Figure 2 shows distance had an effect from 3 ft to 10 ft but then the signals were not meaningfully different from 10 ft until the signal dropped at 65 ft. This is consistent with industry research testing [11]. Therefore, just two distances, 3 ft and 15 ft, were tested further. The distance of 15 feet was chosen as it is representative of the farthest away a device would be from a beacon in an average room [12].

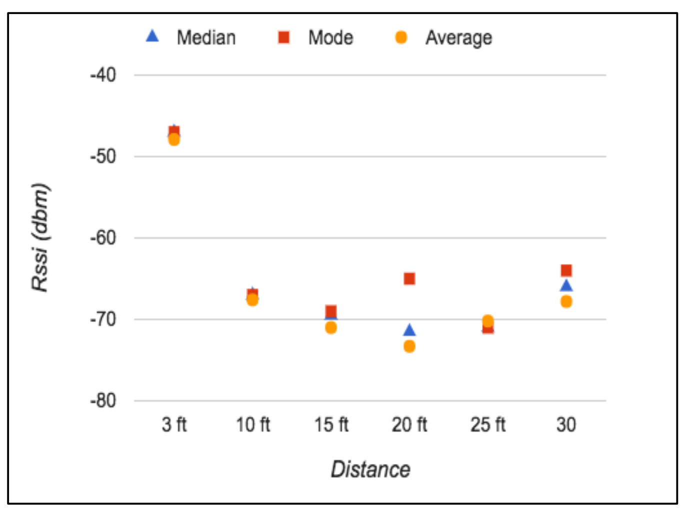

FIGURE 2
EFFECT OF DISTANCE ON RSSI

II. Full Factorial Testing

With location set to "in pocket" and orientation set to "antenna face out," the full factorial experiment investigates all eight combinations of the four levels of obstacles (none, body, door, and wall) and two levels of distance (3 ft and 15 ft). The experiment was performed in an empty gym without noise from other devices. The experiment design is shown in Table 2.

In this experiment, 30 data points were taken 5 seconds apart for each test setup. RSSI was recorded and used to calculate four values: median, mode, average, and standard deviation. The obstacle levels "none" and "body" represent a person in the same room as the beacon, while the obstacle levels "door" and "wall" indicate the device is outside the room containing the beacon. Although this experiment controlled for noise, the RSSI values still fluctuated. Environmental factors in a house will cause the values to have even higher variance than our testing. Therefore, mode was recorded in the data processing to most closely represent the real signal strength and filter noise [11].

TABLE 2
FULL FACTORIAL TESTING SETUP

Test	Obstacle	Distance (ft)	Location	Orientation
Test 1	None	15	Pocket	Face out
Test 2	None	3	Pocket	Face out
Test 3	Body	15	Pocket	Face out
Test 4	Body	3	Pocket	Face out
Test 5	Door	15	Pocket	Face out
Test 6	Door	3	Pocket	Face out
Test 7	Wall	15	Pocket	Face out
Test 8	Wall	3	Pocket	Face out

II. Test Results

Based on the RSSI mode interaction plot for distance and obstacle in Figure 3, no interactions were found and the variables can be analyzed independently.

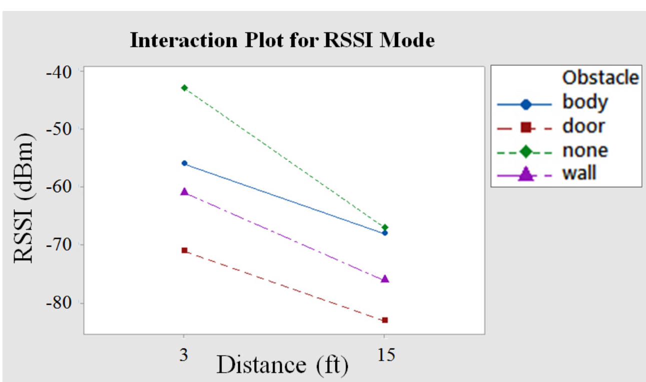

FIGURE 3
INTERACTION PLOT FOR RSSI MODE

RSSI average readings were subjected to a two-way analysis of variance having two levels of distance (3 ft and 15 ft) and four levels of obstacle (none, body, door, and wall). All effects were statistically significant at the .05 significance level. The main effect of distance yielded an F ratio of $F(1,22) = 48.46$, $p < .001$, indicating distance is a significant factor. The main effect of obstacle yields an F ratio of $F(3, 22) = 30.16$, $p < 0.001$, indicating that obstacle is a significant factor. Practically, these test results mean that there was at least one significant level of each factor. What it does not mean is that all combinations of these factors can be differentiated with RSSI.

As shown in Figure 3, a device through a body at 15 feet is read as a weaker RSSI than a device through a wall at 3 feet. Therefore, the system requires a conscious choice of the quantity and placement of beacons in a room. Beacons are required on either side of internal walls to ensure the strongest signal strength will be read from a beacon within the same room as the device. This is to minimize false positive readings caused by detecting a device through a wall. Figure 4 shows the potential beacon placement in a one-story residence.

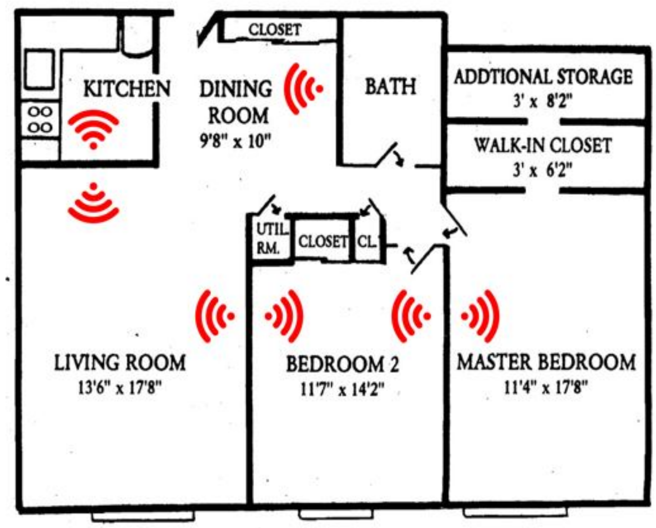

FIGURE 4
POTENTIAL BEACON PLACEMENT

CONCLUSION

This project has demonstrated that Bluetooth Low Energy and beaconing devices can provide micro-location data that increases accuracy and functionality in smart home technologies. By approaching the problem of identifying users in a given room with the Observer-Broadcaster configuration, the system can micro-locate devices beyond just smartphones running user applications, allowing for additional compatibility with wearables. The data flow spanning from collecting advertising packets up to identifying users and analyzing movement within the home has been developed as a proof of concept to demonstrate its feasibility for smart home applications. The test results showed that the system can detect a user's room-level location within a house. A trio of application use cases were considered to explore the value and risks of integrating this non-intrusive BLE technology into home automation.

REFERENCES

[1] Van der Meulen, R. (2015). “Gartner says 6.4 Billion connected ‘Things’ will be in use in 2016” Gartner Newsroom.

[2] Wearable Flexible Lightweight Modular RFID Tag With Integrated Energy Harvester. (2016). IEEE Transactions on Microwave Theory and Techniques, Microwave Theory and Techniques, IEEE Transactions on, IEEE Trans. Microwave Theory Techn, (7), 2304. doi:10.1109/TMTT.2016.2573274

[3] Weber, R. M. (2016). Internet of Things Becomes Next Big Thing. *Journal of Financial Service Professionals*, 70(6), 43-46.

[4] Stadd, 2. A. (2013, April 2). “79% of people 18-44 have their smartphones with them 22 hours a day [STUDY]”. Retrieved February 23, 2017, from http://www.adweek.com/digital/smartphones/

[5] iPhone 7 - Technical Specifications. (n.d.). Retrieved March 29, 2017, from http://www.apple.com/iphone-7/specs/

[6] Lee, J. S., Su, Y. W., & Shen, C. C. (2007). A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi. In *IECON 2007 - 33rd Annual Conference of the IEEE Industrial Electronics Society* (pp. 46–51). https://doi.org/10.1109/IECON.2007.4460126

[7] Yuan Zhuang; Jun Yang; You Li; Longning Qi; Naser El-Sheimy (May 2016). "Smartphone-based indoor localization with Bluetooth low energy beacons." *Sensors (14248220)*, 16 (5), 1-20.

[8] Heydon, R. (2012). Bluetooth low energy: the developer’s handbook. Prentice Hall.

[9] Texas Instruments. (2016, October). CC2640 and CC2650 SimpleLink™ Bluetooth® low energy Software Stack 2.2.1 Developer's Guide. Retrieved March 30, 2017 from http://www.ti.com/lit/ug/swru393d/swru393d.pdf

[10] Argenox Technologies. (n.d.). A BLE Advertising Primer. Retrieved March 30, 2017, from http://www.argenox.com/a-ble-advertising-primer/

[11] Gao, V. (2015, September 21). Proximity And RSSI. Retrieved March 29, 2017, from https://blog.bluetooth.com/proximity-and-rssi

[12] Architecture CAD. (2012, January 15). Room Sizes. Retrieved March 29, 2017 from www2.d125.org/im/ACAD/pdf/room_sizes.pdf

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