ECE 445

Senior Design Laboratory

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Project Proposal

Microcontroller-based Occupancy Monitoring (MOM)

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1 Introduction

1.1 Problem

With the campus returning to normalcy from the pandemic, most, if not all, students have returned to campus for the school year. This means that more and more students will be going to the libraries to study, which also means that the limited space at the libraries will be filled up with the many students who are now back on campus. Even in the semesters during the pandemic, many students have entered libraries such as Grainger to find a place to study, only to leave 5 minutes later because there are no open seats. With the closing of the Undergraduate Library in the Spring 2022 semester, it is likely that this problem will get worse.

Libraries play an essential role in the academic side of the college experience. In a 2015 research survey conducted by Gensler [1], libraries were ranked as the top places for students to study alone and work in a group, with providing quiet space for work ranked as its important resource. However, when there is a lack of study spaces for students, especially during midterm exam periods, this could have a negative impact on students. It could not only reduce the amount of study time available to a student, but it may also reduce motivation to study. As mentioned in an article written by the Daily Bruin, the official student newspaper at the University of California, Los Angeles [2], students have attributed the lack of open study spaces as a cause of unnecessary stress which may affect academic performance.

1.2 Solution

Our solution utilizes a fleet of custom devices that will scan for nearby Wi-Fi and Bluetooth network signals in different areas of a building. Since students nowadays will be using phones and/or laptops that emit Wi-Fi and Bluetooth signals, scanning for Wi-Fi and Bluetooth signals is a good way to estimate the fullness of a building. In an IEEE research article about the effectiveness of using Wi-Fi probe requests to estimate the presence of people [3], the authors found that their proposed method indicated a very strong correlation with the actual number of people present in their environment of study. Our custom devices, which can be deployed in any location near a wall outlet, will be able to scan for these connections. They will then compile occupancy data for their assigned sectors and feed this data into an IoT core in the cloud. This IoT core will send information to a cloud database. The database will connect with our web application which students will use to locate open study spaces without aimlessly searching around campus.

It should be mentioned that other occupancy monitoring products exist, such as the Waitz [4] system from the University of California, San Diego. However, those products rely on the use of hardware that are currently experiencing supply chain issues [5], [6]. Our solution will be using microcontrollers and parts which are inexpensive and readily available.

1.3 Visual Aid

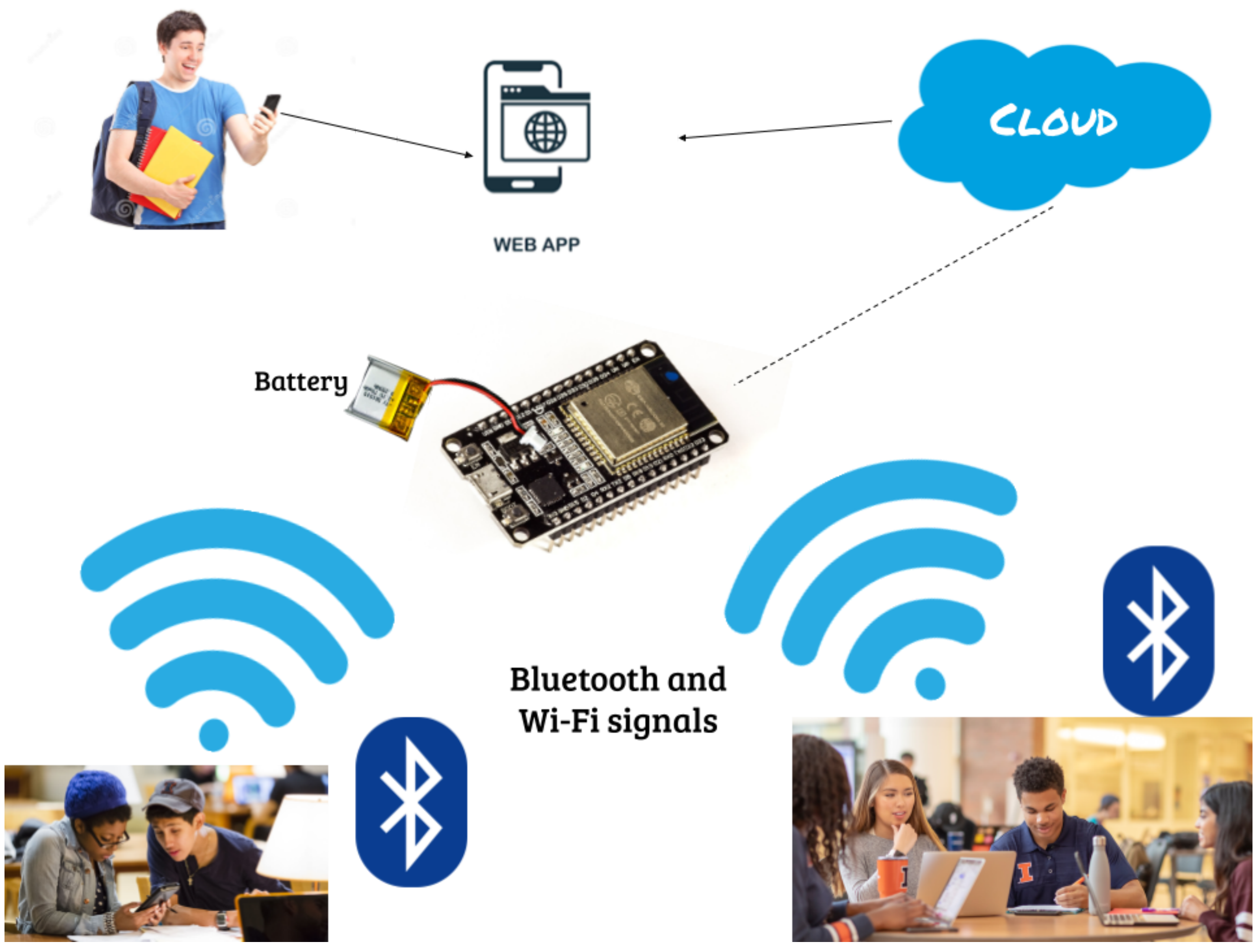

Figure 1: Interactions between nodes, student devices, and web application

1.4 High-Level Requirements

- Each device must be able to estimate sector occupancy with at least 85% accuracy.
- Each device must be able to run indefinitely while plugged into wall power and for at least one hour when unplugged.
- The web app must be able to update the displayed occupancy data every 5 minutes or less.

2 Design

2.1 Block Diagram

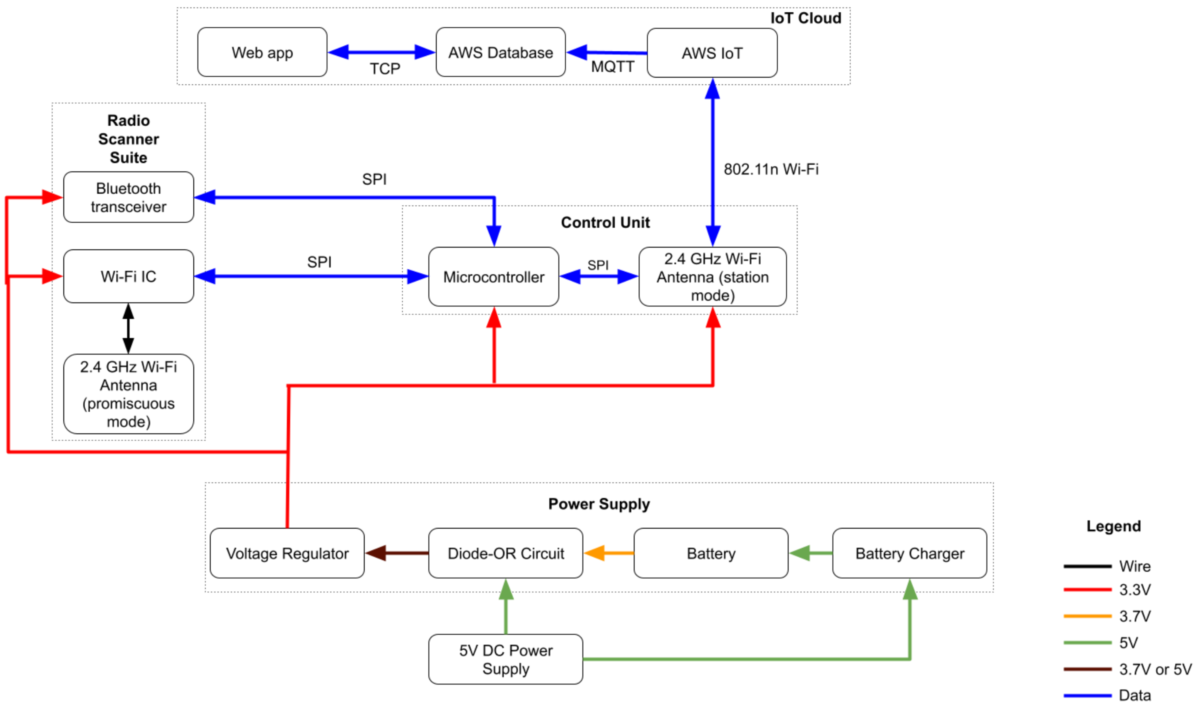

Figure 2: Block Diagram

2.2 Subsystem Overview

2.2.1 Control Unit

The control unit receives information about Wi-Fi and Bluetooth traffic from the Radio Scanner Suite. It will then do some light processing on this data and send it to the IoT Cloud subsystem. This unit is also responsible for programming the microcontroller with the custom software.

2.2.1.1 ESP32 SoC

The ESP32 family of SoCs are mature products that are well-known in the IoT space. For this project an ESP32 was selected as the microcontroller of choice because it is easy to program and contains a very capable microcontroller for not only its price, but also for its low power consumption. It also comes with an integrated 2.4 GHz Wi-Fi module, Bluetooth Low Energy module, and integrated low-profile RF antenna. These will be very useful for the Radio Scanner Suite. The SoC will need to connect to the IoT Cloud subsystem via 802.11n Wi-Fi in order to send occupancy information to the web application.

Requirement 1: The ESP32 must be able to connect to the cloud server, collect occupancy data, and send occupancy data within a 5-minute time interval.
Requirement 2: The ESP32 must be able to connect to IllinoisNet via Wi-Fi with a link speed of at least 5 Mbps.

2.2.1.2 USB-to-UART Bridge

The ESP32 will need to be programmed with our custom software in order for it to work properly. Since the ESP32 is only shipped as the chip itself, this bridge will need to be used to convert USB data into UART signals to program the microcontroller.

Requirement 1: The baud rate of the UART connection needs to be at least 96000.

2.2.2 Radio Scanner Suite

The radio scanner suite is the main subsystem that will be used to measure the occupancy of a sector. Since most, if not all, modern personal devices contain Wi-Fi and Bluetooth modules, we will be monitoring those protocols to estimate occupancy. The radio scanner suite consists of the necessary components for monitoring these types of RF transmissions.

2.2.2.1 Integrated ESP32 Wi-Fi 2.4 GHz Wi-Fi Module

To scan for Wi-Fi traffic, each node will be using the ESP32's integrated 2.4 GHz Wi-Fi module and antenna. The ESP32 can be set to monitor Wi-Fi traffic in promiscuous mode, and there are official library functions that our custom software can utilize as part of our Wi-Fi monitoring algorithm.

Requirement 1: The integrated Wi-Fi module must be able to read and identify Wi-Fi traffic from different clients.

2.2.2.2 Integrated ESP32 Bluetooth Module

To scan for Bluetooth traffic, each node will be using the ESP32's integrated Bluetooth module. There are official library functions created by the developers of the ESP32 that assist in the scanning of Bluetooth traffic. Our custom software can utilize these as a part of our Bluetooth scanning algorithm.

Requirement 1: The integrated Bluetooth module must be able to read and identify Bluetooth traffic from different clients.

2.2.3 Power Supply

The power supply is what powers the Radio Scanner Suite and Control Unit of each node, allowing them to process occupancy data. The power supply will consist of a battery backup so that nodes can continue gathering data if the wall plug is removed.

2.2.3.1 Lithium-Polymer Battery

A battery serves as a power source when the device is not plugged into wall power. If the device is plugged in, the battery will be charging to ensure that it can run if the device becomes unplugged.

Requirement 1: The battery must provide a stable voltage of 3.6V +/- 0.6V.
Requirement 2: When the device is unplugged, the battery must power it for at least one hour.

2.2.3.2 Battery Charger

Should the battery be used, it will need to be recharged to be able to use it again. When the device is connected to wall power, the battery charger sends power to the battery.

Requirement 1: The battery charger must be able to charge the battery to at least 3.7V, but no more than 4.23V, in less than 12 hours.

2.2.3.3 Voltage Regulator

Since the ESP32 has a maximum operating voltage of 3.3V [7], and Lithium-Polymer batteries have a normal voltage of 3.7V, the voltage will need to be stepped-down to prevent damage to the ESP32.

Requirement 1: The voltage regulator must be able to supply a stable voltage of 3.3V +/- 0.3V.

2.2.4 IoT Cloud

The IoT Cloud subsystem receives occupancy data from all nodes, compiles them, and then displays them on the web application for the users to see.

2.2.4.1 AWS IoT

Each one of our nodes will connect to AWS IoT, which allows them to publish occupancy information to the various other AWS services that will be used for the web application.

Requirement 1: Each node should be able to connect to the AWS IoT service with a round-trip latency of no greater than 500 milliseconds.

2.2.4.2 AWS Database

To store and persist the occupancy data, we will need to keep the data in a database. AWS makes this easy by offering a plethora of database management systems that are interconnected with other AWS services, such as AWS IoT.

Requirement 1: The database must be able to update five entries within the span of 30 seconds.
Requirement 2: The total monthly cost of the database instance must be no more than $50.

2.2.4.3 Web Application

The web application is what the users of our project will be interacting with. The frontend of the web application will display the occupancy data, while the backend will query the AWS database for the occupancy data to display to the user. It will need to be responsive and display the information quickly to the user.

Requirement 1: The user interface of the application loads in no more than 10 seconds.
Requirement 2: The user interface must be scalable and readable on smartphones, tablets, laptops, and monitors.

2.3 Tolerance Analysis

The most challenging part of our design is the process of estimating the occupancy of a sector via the Radio Scanner Suite. As Wi-Fi and Bluetooth are wireless communication protocols, it is possible that a node that is assigned to one sector of a building could receive traffic that actually originated from a different sector. One example of this is in a populated, multi-level apartment complex. Not only would a device in one unit be able to detect Wi-Fi traffic that is in a different unit on the same floor, but it can also detect traffic originating from clients on different floors. Our occupancy estimation algorithm would need to account for this in order to keep estimations as accurate as possible. One possible metric that could be used is the Received Signal Strength

Indicator (RSSI), which our custom software can read from the integrated antenna. We can estimate RSSI and its relationship to distance as described in [8]:

$$RSSI = A - 10n \log(\frac{d}{d_0}) - X_\sigma$$

where A is equal to the received transmission power subtracted by the path loss at distance d, n is the path loss index of the environment where the device is deployed, d_0 is the reference distance, and X_σ is the cover factor. If we take a reference distance of $d_0 = 1\ m$ and take multiple measurements for a single client, we can use the following formula to estimate distance:

$$d = 10^{(A-RSSI)\,/\,10n}$$

As we can physically measure the maximum distance between a client and one of our devices in a sector, we can determine a range of RSSI values which indicate if a detected wireless packet originated from the device's assigned sector.

Another part to account for is if a single student has multiple devices that can communicate using Wi-Fi and Bluetooth. This would mean that if we were to perform our occupancy calculations by simply counting the number of unique MAC addresses a node sees, we could be overcounting compared to the actual number of students present in that sector. One method to account for this would again involve using RSSI calculations. If a Wi-Fi and a Bluetooth signal have a very similar RSSI, it can be assumed that the Bluetooth signal corresponds to the same student as the Wi-Fi signal. While we would need to experiment with this once we build our prototype PCB, this is one possible method we could use in our algorithm.

3 Ethics and Safety

One ethical concern we foresee is installing or deploying our project in public spaces (e.g. ECEB, Grainger Library) without people being aware that the device is in operation and “tracking” people situated in the public space. This might violate section 1.6 in ACM’s Code of Ethics [9]. We plan to address this concern by explicitly labeling our devices (with the name of our project, what class and section this device was built for, points of contact, etc.), so we don’t give off the impression that we are recording people’s movements without their permission and consequently violating their personal privacy. We may also introduce an online survey that individuals can fill out anonymously to report any questions or concerns they may have, as well as post signs notifying people of our project.

In addition, while collecting our occupancy data, we plan on collecting no more than the signal strength and originating MAC addresses of transmitted traffic our microcontrollers detect. This is in accordance with section 1.6 in the ACM Code of Ethics [9] to respect privacy by only collecting the minimum amount of personal information necessary to perform the project's function. As we don't need to store MAC address information to estimate occupancy, this information will be retained for no more than 24 hours after collection and will be safely disposed of after that time.

As our project is currently in its very early stages of development, it is imperative that we stay in accordance with section I-5 of the IEEE Code of Ethics [10] and acknowledge and consider all feedback offered to us. This includes feedback offered by other students, teaching assistants, professors, Machine Shop staff, and other professionals in our discipline. As we continue through the development of this project, it is also important to remain honest and realistic in presenting our project's results, capabilities, limitations, and data.

We will make sure to adhere to all the safety regulations and precautions put in place when building the electrical components/portions of our project. That means strictly following the rules and precautions enforced in all of the ECE labs's (ECE Open Lab, etc.) and outlined in the university's laboratory safety training. For instance, always wearing safety goggles and face coverings when soldering or performing other sorts of direct electrical work.

As our design includes the use of a rechargeable battery, we must also test and ensure that the power supply subsystem remains within safe operating parameters. This includes making sure that the rechargeable battery does not overcharge, which could lead to battery explosion [11] and physical harm to others. This directly relates to section I-1 of the IEEE Code of Ethics [10] to protect the health of the public. To prevent this and possible physical harm to others from happening, we will ensure that our battery charger contains a battery charge management controller to properly manage the charge of the battery.

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