Magic Door Sensors

Final Report

Team 18

Daji Qiao (ECpE, ISU)

Mitchell Bratina [Project Plans Engineer]
Calvin Christensen [Engineering Activities Director]
Isaiah Exley-Schuman [Report Manager]
Collin Kauth-Fisher [Team Engineer]
Joseph Kueny [Meeting Facilitator]

sddec20-18@iastate.edu
sddec20-18.sd.ece.iastate.edu

Revised: November 15, 2020

Executive Summary

Development Standards & Practices Used

Hardware

- Enclosure must have an IP rating of IP20 (protection against finger intrusion)
- Device must remain operational within parameters when subject to temperatures between -10C and 40C
- All wireless transmission/reception will comply with FCC laws
- Base station hardware will be primarily PCB based

Software

- Code shall not contain more than one statement in any given line
- Code shall not implement single character variable names except in iterative loops
- Code shall not contain lines of length more than 100 characters
- Code shall follow consistent use of variable naming schemes
    - e.g., camelcase
- Code thall not ignore exceptions
- Each nested block shall be indented more than the previous block

Summary of Initial Requirements

- One base station module and one door module will be designed and physically implemented
- The base station module will interface with a phone application and the door module
- The base station module will notify the phone user when the door has opened, as determined by the system
- The door module will not be powered by battery or by wire
- The system must accurately report "door open" status 99% of the time, and "door closed" status 95% of the time
- The door module must cost less than $70 to produce
- Door module must weigh less than 1 pound and be less than 6"x6" when installed
- Base station must identify door status up to 30' away line of sight, or 10' away through a wall
- System must notify phone user of a door opening within 1 second of the event

    - Must implement a disarming system
- Reporting of door events must be wireless
- Total system cost must be less than $300

Decision to Change Requirements

With the change to entirely virtual collaboration efforts by the university in the Spring semester of 2020 and the desire to continue that for the safety of the team in the Fall semester of 2020, our project had to shift focus to another method of detecting the door state. Our original plan of using RF harvesting was too hardware intensive to be done effectively while working remotely. After Iowa State University went online, we began to look back into the use of a previously discussed idea of using Channel State Information (CSI) from WiFi and machine learning to predict the door state.

From this point, we split into two subteams to work on both the RF Harvesting circuit and the CSI prediction model. This led us to creating a new set of requirements to accommodate the expansion of our project scope with our smaller groups. Most of the shift in requirements resulted in the replacement of the end user interface with the production of a prototype of the door state predicting system.

Summary of Revised Requirements

- A prototype of the RF circuit will be created
    - Supercapcitor charged by an RF harvesting antenna
    - Door state transmitted to Raspberry Pi
- The RF circuit must cost less than $70 to produce
- CSI frame collection will be autonomous
- A prototype of the CSI modeling use will be created
    - Classification model will predict within one second
    - Classification model accuracy will not drop below 90% while maximizing recall score
- RF circuit must weigh less than one pound and be less than 6”x6” when installed
- Base station must identify door status up to 30’ away line of sight, or 10’ away through a wall
- The system must accurately report door status 95% of the time
- Reporting of door events must be wireless
- Base station cost must be less than $300

Applicable Courses from Iowa State University Curriculum

- CPRE 185
- CPRE 288
- CPRE 489
- EE 201
- EE 230
- EE 311

New Skills/Knowledge Acquired Outside of Coursework

- RF Harvesting
- CSI Frame Collection
- Machine Learning Model Creation
- Machine Learning Model Optimization
- Virtual Collaboration

Table of Contents

List of Figures/Tables/Symbols/Definitions

1 Introduction

1.1 Acknowledgement

We would like to acknowledge all the help that we have received from our faculty adviser, Daji Qiao. He met with us regularly and provided us with a stream of new ideas and a surface off of which to bounce our own. He held a genuine interest in the outcome of our project.

1.2 Problem and Project Statement

General Problem Statement

Currently, self-installable home security systems (i.e., Ring ™) utilize many door and window sensors to determine whether those doors or windows are open. These sensors generally report (over wifi) back to a base station that gathers all the state information about the sensors and reports it to a user's device, such as a phone. These sensors require a battery to operate causing the user to replace the battery when it dies. This means that the user cannot "set and forget" his security system. If a user forgets to replace a battery in any one of the sensors in their home, it compromises the integrity of the security system.

General Solution Approach

Our team wants to create a self-installable home security system that does not require any batteries or wires to be used with the sensors. We plan to do this by utilizing RF harvesting so that the devices will be able to be constantly charging. This would remove the requirement of the user to replace batteries and would increase the integrity of the security system. By the end of this project, we hope to produce a base station and a door sensor proof-of-concept. This door sensor will be able to consistently run, while meeting our previously specified requirements, without any sort of battery or wired power. It will also send its status (door open or door closed) to the base station wirelessly. We also plan to utilize Channel State Information (CSI) and machine learning to predict when a door is open by analyzing changes in a Wi-Fi signal.

1.3 Operational Environment

Because our sensors and base station will be within the home, they will not need to withstand many of the so-called "elements." The door sensors will likely be mounted to exterior doors, and the window sensors to exterior windows, so they will be made to withstand a reasonable range of temperatures. They will be charged using RF harvesting and will send their state data wirelessly. The modern home is full of signals of different frequencies, we will need to find ideal frequencies on which to operate our devices. One challenge of CSI is that we will have to make sure natural movements within the home do not interfere with the signals being read.

Another aspect that we will keep in mind throughout our project is the fact that these devices will be within the home, so they should be beautiful looking tech, or at least not displeasing to look at.

1.4 Requirements

Physical

One base station module and one door module will be designed and physically implemented

Door module must weigh less than 1 pound and be less than 6”x6” when installed

Functional

Reporting of door events must be wireless

Base station must identify door status up to 30’ away line of sight, or 10’ away through a wall

The base station module will interface with a phone application and the door module

The base station module will notify the phone user when the door has opened, as determined by the system

The door module will not be powered by battery or by wire

The system must accurately report “door open” status 99% of the time, and “door closed” status 95% of the time

Financial

Total system cost must be less than $300

The door module must cost less than $70 to produce

1.4.1 Engineering Constraints & Non-functional Requirements

Engineering Constraints:

- Human interference with the CSI frame propagation.
- Powercast RF power emitter’s dispersion range limitation.

Non-Functional Requirements:

- The RF circuit must cost less than $70 to produce
- RF circuit must weigh less than one pound and be less than 6”x6” when installed
- Base station cost must be less than $300

1.5 Intended Users and Uses

Our end user base has the potential to be very large. Essentially anyone who wants to protect their home and possessions can use our security system. Because our devices will be designed with a certain placement in mind (i.e. door sensors), the uses will be very specific to how we design them.

As of now, our intended use for the sensors are simply for doors, but with the eventual intent to modify the technology slightly to include use on windows or any opening/closing device. The sensors will be used to detect the open/close state of the door (or other objects later) and will allow the user to view this state by relaying the information to the base station and then their app.

1.6 Assumptions and Limitations

Assumptions

- The sensors will be used indoors
- There will be a readily available powersource for the base station
- The house will have WiFi so that the base station can communicate statuses to users' phones

Limitations

- The base station must accept a wall outlet rated at 120 volts.
- May not have excessive sensors on one base station
- RF harvesting does not provide much power

1.7 Expected End Product and Deliverables

Our end product will be a prototype of the door sensing components. There will be an RF harvesting circuit that will transmit the state of the door, detected by a push button, to the Raspberry Pi. The CSI model prototype will collect CSI frames for multiple door antenna angles, train a model around those frames, and then be able to predict the door's state.

2. Specifications and Analysis

2.1.1 Proposed Approach

We have not tested or tried any methods yet; however, we have two options that we are looking into.

Methods of approaching this problem:

- Using RF Harvesting to power a transmitting circuit.
- Using CSI and machine learning to detect an antenna position to sense if the door is open or closed.

We had intended to start with the RF Harvesting method by first testing the transmitting and receiving of data between the sensor and the base station. Due to the extenuating circumstances caused by Covid-19, however, we will not be able to meet in person to work on our RF harvesting circuit. We will instead be testing CSI and machine learning in our own homes. We do not need as advanced parts to test CSI as we do for RF harvesting. We plan to either have one member of the team (who has all the parts) do the RF harvesting testing on his own, or begin testing when we return to school in the fall.

2.2 Design Analysis

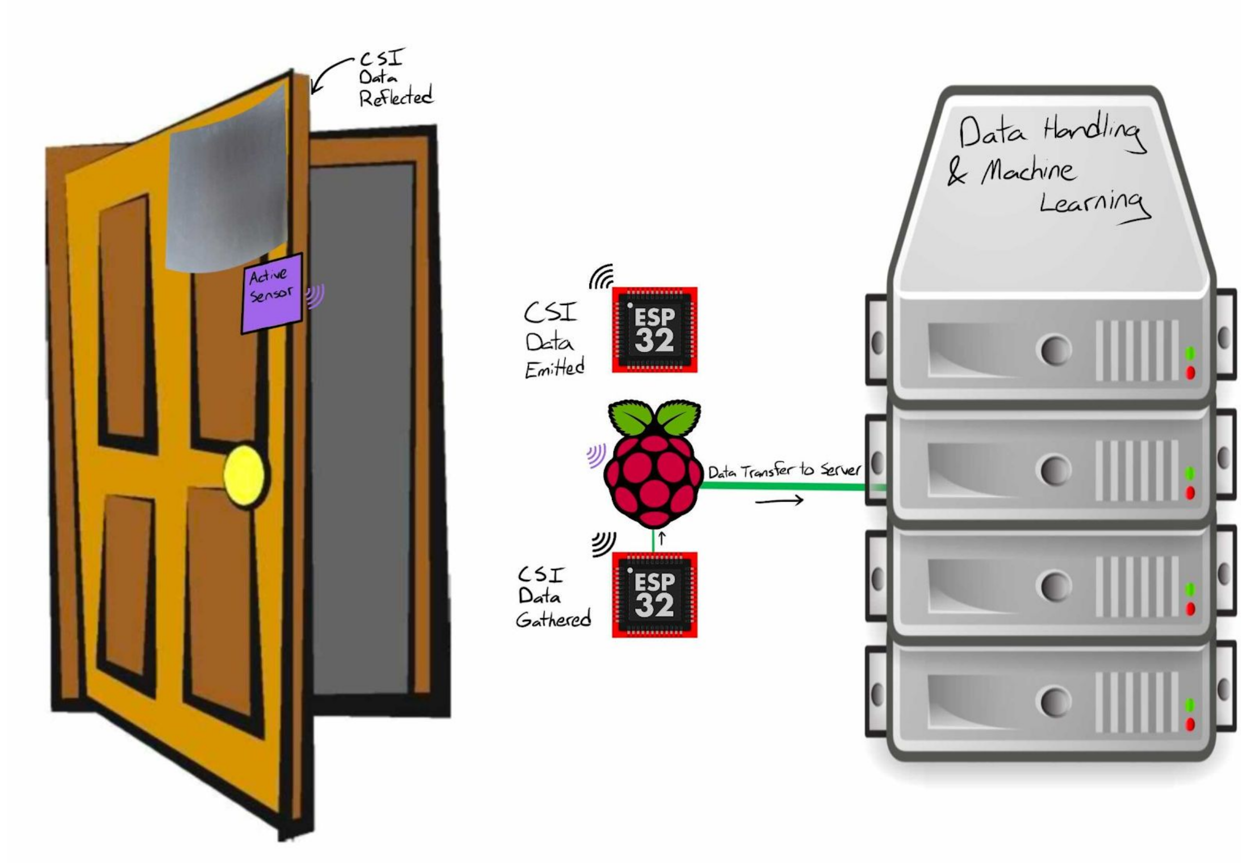
Our RF circuit is at a point where it has the ability to perform its desired action of wirelessly sending the state information back to the base station, but we were unable to acquire the part used to wirelessly charge the device on the door. According to our calculations the device would work using the supercapacitor and RF harvesting technology.

On the other side of our project, we have been able to successfully collect CSI data, use it to train a model, and use that model to predict the state of the door with relatively high accuracy, recall, and precision for an unoptimized model.

2.3 Development Process

Our team will be using the V-Model design process. We believe that this will be the best process for us because we will incrementally have to build new parts upon parts that we have already built. The further we get without testing to be sure we are meeting our requirements and the customers' needs, the further back we will need to go in our process to correct any problems that arise. This means it will be to our benefit to constantly test our parts, prototypes, and product. Because our supervisor is also our client, this will make it easy to have a constant feedback loop on what we are accomplishing.

2.4 Rough Project Diagram



3. Statement of Work

3.1 Previous Work And Literature

There are currently no completely self-sufficient security sensors in the market, but there have been other attempts at remote RF powered devices which we are basing our project on. One such previous attempt was a senior design project from ISU in the fall of 2019. There was a group that tried to collect power from an average home router, but a big problem with it was that the effective distance was only a few inches. This project is not very similar to what we are trying to accomplish, but studying their antenna design may help us with our approach in using CSI.

3.2 Technology Considerations

A strength in our project's technologies that we will be able to play off of is the existence of parts meant for more general tasks similar to what we want to do. There are parts that we have ordered that have been built to assist in RF harvesting and CSI. A weakness we have however is that the restriction on cost is going to require us to be more conservative in what we use. We believe, however, that the parts we have acquired will be able to get the job done. Another weakness in relation to our technology is that our team has not done much in the past with some of the parts with which we will be working. We will have to spend more time learning about these parts.

3.3 Task Decomposition

We essentially split our team into two subteams: a CSI and ML team and an RF circuit team.

Within the CSI and ML team we broke the final goal down into a few tasks:

- Collecting CSI data
- Cleaning and preprocessing the CSI data
- Writing an ML algorithm to predict the door state
- Using the cleaned data to train and test the ML algorithm

There was much interdependence between these tasks. The ML algorithm that we wrote required the data from the CSI collection and the data cleaning needed to format the data into a usable way for the ML algorithm. Finally, once the first three tasks were completed, we were able to train and test the algorithm.

Some of the tasks on the RF circuit team side included:

- Drawing schematics and performing calculations
- Collecting parts and soldering them together
- Writing code for the circuit
- Testing functionality and operating conditions

These tasks were fairly dependent in the order they are above. First we needed to design the circuit, then we built it and coded it, and finally we were able to perform testing.

3.4 Possible Risks And Risk Management

Cost of the system and power collection abilities will be our most limiting aspects at this point in our project. If the parts that we ordered do not meet our needs, the parts that we would have to purchase instead would most likely be more expensive. This causes us to run the risk of increasing our cost dramatically. The power collection abilities run along with this because, at the moment, this seems like the area that has the highest risk of failure.

Another risk that we run is not meeting some of our originally intended deadlines. Now that we are all separated and have to meet virtually due to Covid-19, it makes it difficult to work on hardware. We run a very high risk of not completing all of our hardware-intensive tasks.

3.5 Project Proposed Milestones and Evaluation Criteria

Three milestones that we have discussed so far are related to the components of our project:

1. Have the ability to read the state of a door (through CSI and/or RF harvesting)
2. Have a base station to receive sensor transmissions and handle the statuses.

Milestones 1 and 2 will run together when using CSI because the base station will be transmitting signals that will be reflected by the antenna on the door to find out the state of the door. This will be easy to verify that it is working because we can simply open and close the door. We will, however, need to be able to sense the door is open correctly 95% of the time.

When utilizing RF harvesting, milestones 1 and 2 will be able to be more separated. When correctly powered, we can connect directly to the sensor module and check the state of the door that would be sent if we were attempting to transmit wirelessly. Then when we have accomplished milestone 1, we can start transmitting that state information to the base station to complete milestone 2. As will CSI, it should not be difficult to test as long as we keep in mind our requirements.

3.6 Project Tracking Procedures

We will be using GitLab Issues to track progress. This will involve creating an issue for each task that needs to be completed. The procedure for these issues will involve regular meetings where we create new issues, assign issues that need to be completed/worked on in the coming cycle until our next meeting, update the group on progress of in-progress issues, and review completed issues to verify that they have satisfied the original intent and desired changes the issued required. Because our project is largely hardware based, we will not need to greatly utilize software branches outside of our server work, but within that area, we do intend to create work branches for each server issue and to merge this into a main release branch when they are working as intended.

3.7 Expected Results and Validation

The end result will have a button that requires no attached power source. When the door is closed in the door frame, the button will be pressed and will know that the door is closed. Our door sensors will utilize both RF harvesting and CSI in order to increase the accuracy of the open/close reading. Our system will have an antenna to aid with CSI, a base station in the home for local arming/disarming, CSI collection and RF signal sending to power the RF harvesting sensor, and information relaying. At a high level, we can test the system as a whole by setting up the system in one of our real homes and checking to see that it all works as expected. A deeper validation will require a statistically significant number of open/close cycles to verify that we are meeting the required accuracy of the sensors.

4. Project Timeline, Estimated Resources, and Challenges

4.1 Project Timeline

Week Zero	Week One	Week Two	Week Three	Week Four
Collect CSI Frame Data				
Format CSI Frame				
	Machine Learning Model Development & Optimization			

Our Gantt chart was created to be generic for the time being, because we are not sure when each team member will have the parts to start individual development. Once we have the components, then we will be in Week Zero, and we can start from there. This is our idealistic chart for the rest of the semester, and we do not have a Gantt chart for the upcoming semester because it is unknown what circumstances will be surrounding it.

The work done up to the point of Week Zero has been researching the possible technologies that we can use and trying to get parts from the ETG. The issues we had getting components ordered and in our hands took up a majority of the time until our access to labs was restricted. This meant we could no longer continue with our original timeline which involved working on the RF circuit.

4.2 Feasibility Assessment

The project will be a prototype of a home security system that does not require intermediate involvement for sustainability. The largest issue with the project is maintaining power to door sensors throughout a house. The other issue we will have is the lack of access to campus resources for the academic year.

4.3 Personal Effort Requirements

Joseph Kueny - Worked on Raspberry Pi and ESP32 connection, designed rudimentary antenna, researched backscatter wifi, collected CSI data, tested ML classification models, determined metrics for optimization.

Calvin Christensen - Worked on Raspberry Pi and ESP32 connection, researched RF power harvesting technologies, worked on capacitor testing.

Mitchell Bratina - Researched RF circuit components, worked on capacitor testing, researched backscatter wifi, cleaned and preprocessed CSI data, wrote, trained, and tested machine learning algorithms, wrote real-time capable training and classification program.

Isaiah Exley-Schuman - Researched RF circuit components, designed preliminary RF circuit, worked on capacitor testing, designed final RF circuit, built final prototype, performed testing on final circuit.

Collin Kauth-Fisher - Developed server for client integration, worked on Raspberry Pi and ESP32 connection, ran sample CSI programs, designed CSI collection scripts, worked on data handling, created live model demo.

4.4 Other Resource Requirements

Item Number	Manufacturer Part #	Digi-Key Number (If applicable)	Description	Cost in USD	Quantity
0	ATTINY85-20PU	ATTINY85-20PU-ND	IC MCU 8BIT 8KB FLASH 8DIP	1.20	3
1	DK-6R3D105T	604-1018-ND	CAP 1F -20% +80% 6.3V T/H	4.27	1
2	KR-5R5C104-R	283-2806-ND	CAP 100MF -20% +80% 5.5V T/H	3.17	1
3	KR-5R5V474-R	283-2815-ND	CAP 470MF -20% +80% 5.5V T/H	5.53	1
4	PHV-5R4H155-R	283-4206-ND	CAP 1.5F -10% +30% 5.4V T/H	10.65	1
5	MX-FS-03V	-	HiLetgo 315Mhz RF Transmitter and Receiver Module	4.69	1
6	PGM-11801	1568-1079-ND	TINY AVR PROGRAMMER	16.25	1
7	-	-	ESP-32 Development Board	7.50	2
8			Raspberry Pi	55.00	1
			Total Cost	$114.56	

4.5 Financial Requirements

We have a budget of $500. In the above Resource Requirements section, we have listed each part and its respective cost and quantity. As shown, with our current costs, we are well under this $500 limit at $114.56. This gives us quite a bit of wiggle room to continue to experiment in the future if needed or to produce a few prototypes.

5. Testing and Implementation

We were able to do quite a bit of testing for both the CSI and ML side and the RF circuit side. This testing included both functional and non-functional testing including, but not limited to, accuracy of ML models, speed of CSI data collection, RF circuit power draw. More in depth descriptions of testing can be found below.

5.1.1 Interface Specifications

Our interfacing tests would have been involved the most in the RF circuit. We will need to build the circuit and develop the lowest resource intensive software, so that we can determine the level of RF power we will need to supply the circuit.

The other interfacing test that we will need to complete is the interfacing of the door state calculated by the Raspberry Pi and the server for client connection.

5.2 Hardware and software

Hardware we required for our testing were a voltmeter and a function generator. These were useful because we needed to be able to charge and discharge our capacitors to find out how it would be able to power our sensors.

For the testing of the ML models, we had to use high-end personal computers to train and test the models within a reasonable amount of time.

5.3 Functional Testing

For each ML model that we ran, we checked the accuracy score, the recall score, and the precision score. For our later and more promising models, we performed tests with up to 50 runs to find the average of these specifications.

5.4 Non-Functional Testing

We were able to do a slight amount of testing with our capacitors right before leaving Iowa State. We tested how quickly power was released from a capacitor after it was disconnected from a source and were pleasantly surprised to find that it released at a good rate and held a change for longer than expected. This is important to our project because we want to use the capacitor to power a sensor when a door is opened or closed and it will have to be able to be powered up while the door is not in use.

For each ML model that we ran, we ran multiple variations of the models to optimize for recall score.

5.5 Process

Process for Classification Models:

1. Get fresh data
2. Run model to get statistics
3. Refine model and retest with new training data
4. Repeat steps 2 and 3 to improve accuracy and recall

Process for RF Circuit:

1. Create circuit schematics
2. Write code for the transmission logic
3. Create physical circuit
4. Test operating conditions
    a. Power draw

5.6 Results

The 1.5F capacitor will be sufficient for our project. The optimal classification model that we have developed will be a Random Forest model. This model gave us an accuracy of 89.79% and recall score of 97.17%.

6. Closing Material

6.1 Conclusion

After performing system creation and testing, we have come to the conclusion that, while we were not able to get a complete final working system, both CSI ML and RF harvesting and detection seem to be promising. Given more time to refine and optimize our ML models, we believe that we could greatly improve the accuracy and recall to more acceptable security levels. The RF circuit also did an excellent job of reporting the door state and we believe that if we had the correct parts for the RF harvesting, we could have created a wirelessly charging sensor for the door.

6.2 References

http://sddec19-21.sd.ece.iastate.edu/