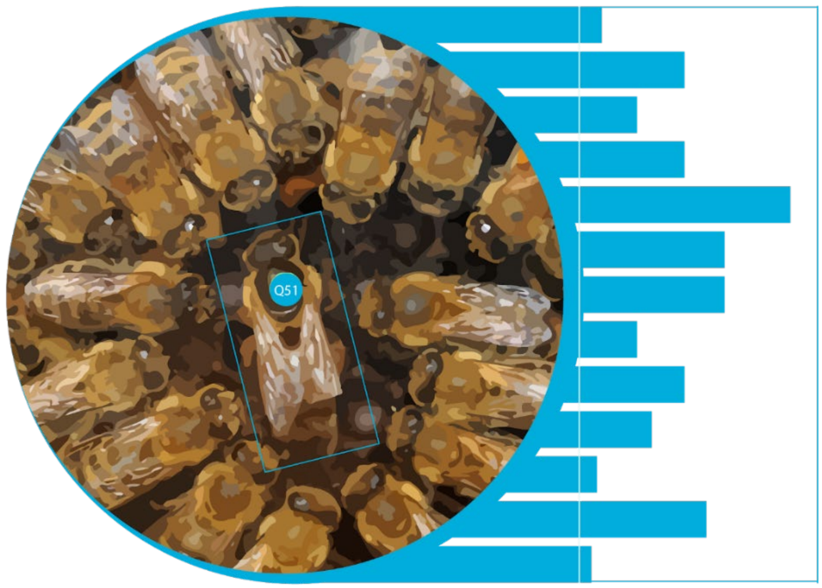
Project Documentation

# Plan Bee

*Commercial Beehive Health-Tracking Solution*
*Utilizing Novel Internet-of-Things Sub-1GHz Communications Template*





**University of Central Florida**
**Department of Electrical and Computer Engineering**

Dr. Lei Wei
Senior Design I

**Group 3**

Tariq Ausaf – Electrical Engineering
Giovanny Reyes – Electrical Engineering
Yannick Roberts – Electrical Engineering
Katelyn Winters – Electrical Engineering



**We would like to thank Steven Eisele at Pollination USA for fully sponsoring Plan Bee.**

# Table of Contents

## Table of Figures

## Executive Summary

The global market of connected devices is estimated to exceed $7.1 trillion by 2020. As such, the demand for a general-purpose asset tracking solution may be significant enough for an entirely new market segment to emerge. A cost-effective device capable of gathering data from a series of connected sensors and broadcasting this information to the cloud for further analysis. Plan Bee aims to accomplish this task.

Our project is focused on the creation of an Internet-of-Things Sub-1Ghz Communications Template and – because we are being fully funded by the commercial apiary Pollination USA – retrofitting this with sensors for monitoring the health and outputs of remote, commercial beehives. This project will cover MEMS and sensors technology to achieve tracking of metrics; this will include but not be limited to RF design and integration of a GPS locator, load cells, a thermistor, a humidity sensor, accelerometers and vibration sensors. The hardware technologies will be weatherproofed for placement upon the commercial beehives. IBM Watson will be discussed and used for intelligent algorithms, and Amazon AWS will be shown used for the storage and manipulation of the apiary's data. Other web technologies will be shown used to create an application "dashboard" for the commercial apiary.

Presented in this document is the implementation details required to develop a connected device capable of funneling sensory data across a secured internet connection to a cloud connected database for analysis and logistical planning.

[word count: 234]

# Project Description

This section is effectively a project overview, including: the motivation and application of our project, much of which was taken from interviewing Steven Eisele and other beekeepers and further market research; a technology-in-development overview to describe our technology-related goals; project illustrations and block diagrams including Power, Hardware and Software stack; requirements specifications including the House of Quality and a short description of our metrics, and how we plan to demo specific engineering specifications in front of committee; and related work, including research papers, prior art (US Patents), and on-the-market available products.

*Note that this chapter is heavy with beekeeping terminology and other industry-related jargon, especially within the motivation. Because of this, we strongly recommend the reading of Appendix A3. Beekeeping Terminology, a short one-page summary on the usage of beekeeping jargon, before delving into this section.*

## Motivation

It is understood that bees are a vital component of the ecosystem. Many flowering, food-producing crops are reliant upon bees for reproduction through pollination. [1] Honeybees are responsible for pollinating greater than thirty-percent of food crops grown in the United States each year. [2] Honeybees are productive members of the agriculture ecosystem. As such, Beekeepers – Apiarists – are of vital importance to the agriculture economy, and thus the national security of the United States as well.

Commercial honeybees, which accomplish the bulk of the pollination of U.S. agricultural farms, are facing problems in today's changing climate. The hives are kept in yard-arrangements, and yards are kept distanced from each other. Five-thousand individual hives are usually spread across one-hundred-square-miles. [3] And these hives are all remotely located, and usually in extreme environments, making maintenance and upkeep of every individual hive unfeasible economically.

Like humans, the health of a beehive factors into account many different individual bees – like cells – that work best unanimously when healthy, and at the mercy of disease and pests. Over the past several years, on average, beehives have been dying at a rate of about thirty-percent-per-year. [4] This is largely due to several health concerns beehives face: pests including varroa mites and small hive beetles; diseases including Colony Collapse Disorder and bacterial, viral and fungal infections; and invaders including other aggressive, territorial beehives, and Africanized bees. [5]

Steven Eisele, our sponsor, has noted that the state governments keeps a census record of individual beehives and patterns, and reimburses commercial apiaries for individual hive losses each quarter. He noted that he would like to see a system for each individual beehive health monitoring, for reasons stated above, that keeps track of the:

- Weight,
- Feeding schedule,
- Medication schedule,
- Location of beehive (GPS),

- Humidity, and
- Temperature.

Hive weight and its rate-of-change (delta) is the single most important statistic to track for commercial apiaries. [6] Constant weight tracking gives the beekeeper information on when the bees are leaving (at dawn) and resting (at night) in the hive, how many bees are active within the hive, and the amassing of honey within the hive until the S-curve levels, when it is time to harvest.

Feeding and medication schedules need to be tracked, as well as a running tabulation of the last time each hive was last fed and medicated and by whom. Inefficiencies in hive maintenance that are currently present – like revisiting already-maintained hives – need to be eliminated, as it wastes company resources including time, food, and medication. The running tabulation keeps track of the last person to deal with each individual hive, eliminating any ambiguity in what work was done by whom and when.

During transportation to contract location and during contract duration, live location of the physical beehive (GPS) needs to be tracked by both the beekeeper and customer. This is important because of the high frequency with which these beehives are relocated, during which they are often lost or stolen. Precise location tracking is one proposed solution to this problem.

Honeybees optimally need to maintain a brood nesting temperature between 32 – 35 degrees Celsius for growth. [7] Temperature fluctuation of about 15 degrees in either direction from these temperatures is acceptable, because of mechanisms bees have developed to regulate hive temperature. Without brooding, it is acceptable for temperatures to range from about 0 – 50 degrees Celsius.

Similarly, relative humidity between 50 – 60% is optimal for brood nesting, while outside of brooding through 20% - 100% relative humidity is acceptable. [8] During brooding then, it is especially important to track temperature and humidity within the hive.

Stretch goals that we have discussed with Mr. Eisele also included:
- Location of the queen bee,
- Listening to the communication of the honeybees
- Pheromones present within the hive,
- Chemicals present within the honey, and a
- Feeding and Medication Control System that automates non-health maintenance of the individual beehives.

The queen bee is the heart of the hive; wherever she goes, the hive follows. And when swarming occurs, she is the orchestrator and lead. When bees swarm, if the queen bee is being properly tracked, the beehive can be found and relocated into a new apiary.

Honeybee colony vibrational measurements highlight the brood cycle. [9] Honeybees displaying dance communication behavior within the colony – the frequency of which generates a corresponding electrical impulse in the bee's antenna – gives information about quality of a food source, temperature, a need for water, the condition of the hive, and the condition of the queen bee. [10] Sensitive vibration sensors can detect the frequency at which certain bees are communicating, as well as the amplitude and deviation around each frequency. Trophallaxis – accomplished by exchange of pheromones – can be used to communicate the same information. It can also communicate that invaders and pests are present. [11] Pheromone sensors within the hive could thus give the apiarist information about the state of the bees within the beehive.

Honey texture is sensitive to the chemicals present within the honey. The color, flavor and aroma ("texture") of honey differs depending upon the nectar of flowers visited by the bees that made it. [12] For example, a hibiscus farm nearby to the colony would produce a light yellow-pink honey, with hibiscus-reminiscent aroma and a mild of the hibiscus flower - a honey varietal. It is important for the apiarist to keep track of honey varietals produced by a colony.

These beehive statistics would be presented in a browser through website featuring a login portal, or through a phone application available through the app store. He would additionally like to receive alerts when the status of his hives change. For example, when honey is ready to be harvested, when it is time for feeding or medication, when humidity or temperature could affect the beehive health, when the individual beehives are moved, and so forth.

## Technology-in-Development Overview

The global market of connected devices is estimated to be valued at more than $7.1 trillion by 2020. [13] As such, the demand for a general-purpose asset tracking solution may be significant enough for an entirely new market segment to emerge. A cost-effective device capable of gathering data from a series of connected sensors and broadcasting this information to the cloud for further analysis. Our technology-in-development is aimed at accomplishing this task, generally appropriate for most Internet-of-Things application. Our technology is a general Commercial Sub-1Ghz Communications Template. We will focus on implementation details required to develop our technology, with the capability of funneling sensory data across a secured internet connection to a cloud connected database for analysis and logistical planning.

## Project Illustration

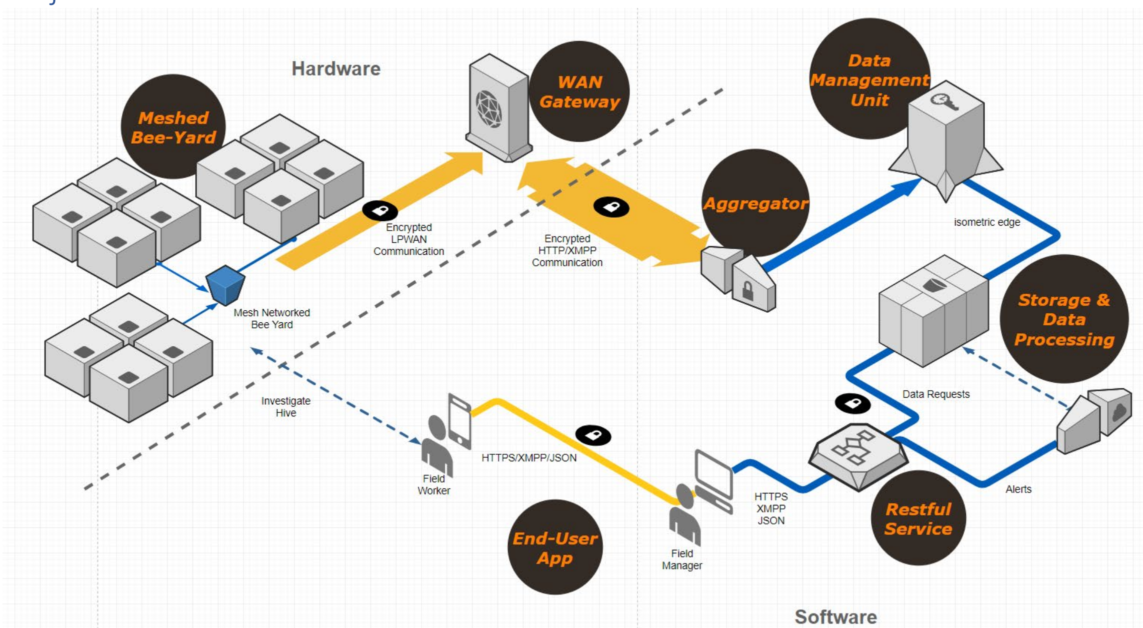



*Figure 0-1: Technology in Development Overview*

Project Bee will be focused on the hardware portion, as defined in the illustration above. Accordingly, a private server will be used to emulate the entire software portion. This includes the web application aggregator and data management unit. Various cloud-based tools will be researched for their feasibility, given the time constraint required to complete the design. While a PCB will be developed for the hardware tracking device, the WAN Gateway will be made using off the shelf modules which are compatible with some single-board-computer devices such as the Raspberry Pi. The gateway will also use wired ethernet to communicate with the internet. In an ideal scenario, a gateway may feature numerous ways of connecting to the internet, notably, cellular, Wi-Fi, satellite or one of the many IOT standards being deployed.

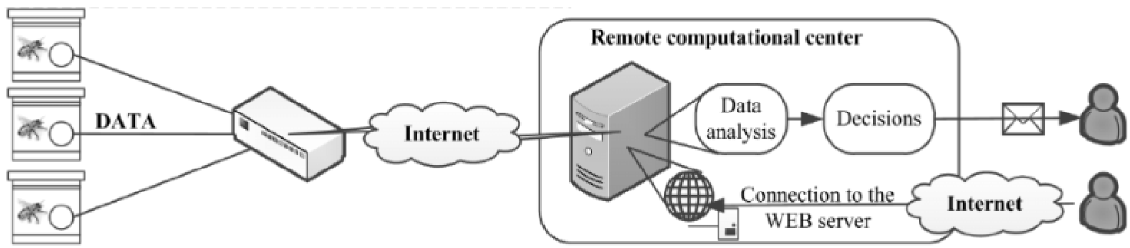
## Related Work

### Research Papers

#### *Communications Technology as Applied to Honeybees*

While there is research available which attempts to track individual hives, some projects focus on tracking the individual bees themselves. This type of data collection contains drawbacks such as price, lack of reliability, and uninformative data. Tracking individual bees is mostly done with different types of radar. A common example of this is harmonic radar. Harmonic radar is only useful for tracking one specimen at a time. Considering bees do not all pollinate in the same area as each other at the same time, tracking one individual bee would be insufficient for attaining information such as pollination routes, etc. Considering that these methods are also extremely expensive to create and reproduce, Plan Bee elected to not follow that route for the current project. There is a focus on obtaining useful data, and an excess of information would be more confusing for apiarists.

Other areas to consider are separate ways to remotely access the data collected. A paper on System Architectures for Real-Time Bee Colony Temperature Monitoring (System Architecture for Real Time Bee Colony, n.d.) goes in depth into many possible ways of uploading data from a source. Plan Bee is focused on remote data extraction; because of this, one specific idea stood out in this article. This is the idea to upload the data attained from each individual hive to an interface device, such as a Raspberry Pi or Arduino. The data would then be transmitted from this device to a server, such as the cloud, using the internet. An example of this is given below.




Plan Bee's design is very similar to this idea. Plan Bee, however, will be using the Texas Instrument CC1352R included on a prototyping board for the gateway. The Simple Link Texas Instrument board will be bought for testing; Plan Bee will then create a board based off this design. Using this technology will essentially be like creating a home-made Raspberry Pi. Some prototyping boards will include sensor arrays; these boards will communicate with the boards used for gateway connection via the CC1352R chip included on each board. Including these chips on all boards will create a mesh network. This will help with an autonomous set-up of yards; yards will not have to be manually designed. All these boards will also include GPS so that each individual hive is trackable no matter what happens.

The connections to the gateway is an important process, but the gateway will also connect to the server using cellular networks. The server database Plan Bee plans to use is Amazon AWS. This system is cheap to use and is a powerful data processor that even includes artificial intelligence tools. The data will then be processed on this server. A webpage or hosted application will then be used to help make the data easily accessible to the customer.

## Prior Art

### *for Beehive Monitoring Systems*

US Patent 20170079249 discusses how certain conditions inside and outside of a bee hive can be monitored and collected using a control system. This data can be compared to reference points of information to determine the meaning behind the data gathered. Measurement of the number of bees entering and leaving a hive is one of the variables monitored, as well as environmental conditions the hive faces. A variety of sensors can be attached to the control system for multitudes of data obtaining purposes, such as temperature measurements and humidity calculations.

US Patent 20070224914A1 discusses how the acoustics of bees and their interaction with the surrounding hive can be monitored and analyzed to determine if there are any airborne toxins affecting the bees. This idea has been patented since 2006; the patent uses specific statistical data to classify certain acoustic sounds that can be affected by air compound.

These classifications can lead to different determinations about the conditions of bees in a hive and the air surrounding those bees. Speculations can be made, such as whether the bees are being affected by mites, or whether the bees are mating. Sounds are sampled for a period using the patented device; these sounds are then translated into frequencies. The obtained frequencies can then be compared to other frequency data statistics to determine the meaning behind the specific frequencies collected.

### *for Establishing Groups of Internet-of-Things Devices*

US Patent 20140241354A1 discusses how any devices that interact with the Internet of Things (IoT) may be connected to form a larger hub of interconnected devices. Communication between these individual groups of IoT devices becomes possible, as well as contact between the more similar devices, therefore expanding the access and abilities of all devices connected on this plane. As an example, one could get information not only about temperature and relative humidity in their house from one IoT sensors group and retrieve information about their electricity usage through IoT-enabled breaker group, accessing all of this data from the comfort of their iPad, anywhere in the world. Criteria is put in place to help make the devices that connect reasonably useful to the consumers using the IoT in this way.

It is worth noting that the use of this patent is almost unavoidable when constructing a recent technology. Having the inner workings of the device Plan Bee is building interconnected would be extremely useful to the finished product. Saving time and money, this patent would really help improve efficiency.

## Market Products

### *Beehive GPS Trackers*

There are several comparable products to our own communications template. FindMyHive offers a similar hive tracking product, with distinct differences involved in the technological build. FindMyHive only offers GPS tracking of hives, and uses a 3G network connection utilizing GSM standards, to cell towers to transmit data to the system connected over the internet. The distance that the trackers can be from any singular cell tower is thirty kilometers. We expect to have a cell-tower-independent data retrieval solution so that apiaries that are more off-grid can still collect data when needed, without having to go directly to the site. Also, FindMyHive only reports GPS tracking once per day. This is not a helpful preventative measure for things like theft, which Plan Bee anticipates addressing with the prototype design. Find My Hive does have a motion activated perimeter for triggering an alarm, but this is an expensive solution that can be improved upon. Any motion could trigger this sensor, causing many false alarms. Plan Bee expects its device to send a notification to the customer when it is moved too far from the originally specified location. FindMyHive is also not offered in the United States to date.

BuzzTech similarly utilizes GPS tracking to enable periodic location updates to the apiarist. The major problem with their solution, according to Steven Eisele, is the size and the cost. The size of the device is larger than absolute necessary and inhibits honeybee movement around the hive. This will cause swarming, at some point. The cost of implementation, according the BuzzTech, is $30 USD per hive per month, more than the cost of food for tracking of just one metric – location. BuzzTech is also only available in the New Zealand market due to several international standards for communications and GPS tracking that inhibit new market entry. We offer several improvements, firstly being available in the United States. We will also be implementing our beehive-aimed communications template in a much smaller package, that will be easily retrofitted on the side of commercial hives; our template will be much less costly per month and have a similar one-time fee for order. And we will offer many metrics rather than just GPS. As well, we are using different standards for communications, location services, and additional metrics for security monitoring.

Save Bees products are focused on preventing hive-theft. The anti-theft device is designed to conserve battery by staying off until it is moved in the slightest, using an accelerometer; the device will turn on and notify the customer of the movement. This is an interesting take on anti-theft because of how long battery life lasts under cited conditions, but there are a few potential problems worth considering. This technology is too sensitive to be practical; if the hive is jostled in the slightest it will falsely alert the consumer. One solution to this problem that we are integrating, is an algorithm that integrates the accelerometer with the GPS in order to determine if the hive is not only vibrated, but relocated more than a trivial distance, yet to be determined. Our devices would not be planted in every hive necessarily. If apiarists could not monitor every hive, the security is not foolproof.

### *Beehive Health Monitoring Solutions*

There are Hive tracking systems in the industry that include much more than GPS and anti-theft precautions. Probably the most similar to Plan Bee's design is Solution Bee's product, the 'B-ware HiveHub' monitoring system. This American based product has similar data transfer tactics to Plan Bee's; the data can be collected with a solar powered device that is then uploaded to a type of gateway for access. This is very much like Plan Bee's design, except the distance the data can be accessed is much greater for Plan Bee. Solution Bee can only access the data up to 1000 ft, or a 30-meter range, using Wi-Fi. This is a much smaller distance than Plan Bee's proposed distance, which is around 10 miles. Solution Bee's 'HiveHub' is also very large and therefore bulky. Such a design is not very efficient to apply to every single hive; Plan Bee is focused on creating a more compact and versatile design that is more equipped for lengthy outdoor use. This Solution Bee product is also much more expensive than the marketable design Plan Bee is creating. Over-all, Plan Bee has a step-up on the technology and overall engineering of the hive tracking process.

Hive Tracks provides a user-friendly interface with an aim to simplify hive management. An interesting idea that Hive Tracks puts forward is for the data collected from each device to be uploaded to a communal database. This would allow the apiarists to see multitudes of data, helping not only themselves and their hives, but the apiary community as well. Collecting this much reliable data would help the research community understand why bees are struggling to survive. In the future, Plan Bee would like to utilize this basic concept as well; bee survival is a priority in a market that relies so heavily on these dying animals. This product is also more reasonably priced than other available hive tracking technologies on the market. Hive Tracks puts up a good front, but it is extremely difficult to access essential information about what the product really does. Data sheets are not available for consideration before purchasing the product; trial and error seems to be the only way to get a good feel for the system the company offers. Customers in the past have reported a glitchy mobile application system, as well as missing key features such as a to-do for apiarists.

#### *Beehive Metrics Tracking Software*

Hivetrack – not Hive Tracks, which was discussed earlier – offers its user a free platform to record inspection data. Data entries are available for queen color, type and existing hives, for hive type and queen relationships, for queen family tree and inspection history of the hive, including feed and medication, weight and honey production. This is the most basic way to utilize technology to keep track of apiaries, none of the processes have been streamlined. We aim to streamline these data-recording processes and use a much more advanced and modular (customizable) data dashboard, setting us apart from Hivetrack.

Bee Cloud pride themselves on their easy to use software. Allowing users to change around yards with ease and manage many several aspects of data organization is extremely useful. Plan Bee also expects to have a very efficient and user-friendly interface for organizing electronically obtained data. Combining software design aspects like Bee Cloud has with more physical properties, such as Buzz Tech's hive trackers, is the most well-rounded technique for helping customers manage their apiaries with ease. Improving on both techniques is also a priority for Plan Bee. For example, Bee Cloud does not yet connect to mobile devices or tablets. Plan Bee's data collecting technique should allow mobile devices to connect to the data infrastructure directly.

## Requirement Specifications

### House of Quality

The illustration below contrasts the project's engineering requirements against a set of marketing requirements. The notable engineering requirement were limited to a set of 7 items which were considered crucial in accomplishing the design priorities set forth by this document. In contrast, the marketing requirements were obtained by inquiring about the most regarded features from actual beekeepers seeking such a product. Given this information, the house of quality was developed to underscore the relationship between engineering development capabilities and consumer need. Understanding this diagram will further align the project goals with that of the end-user.

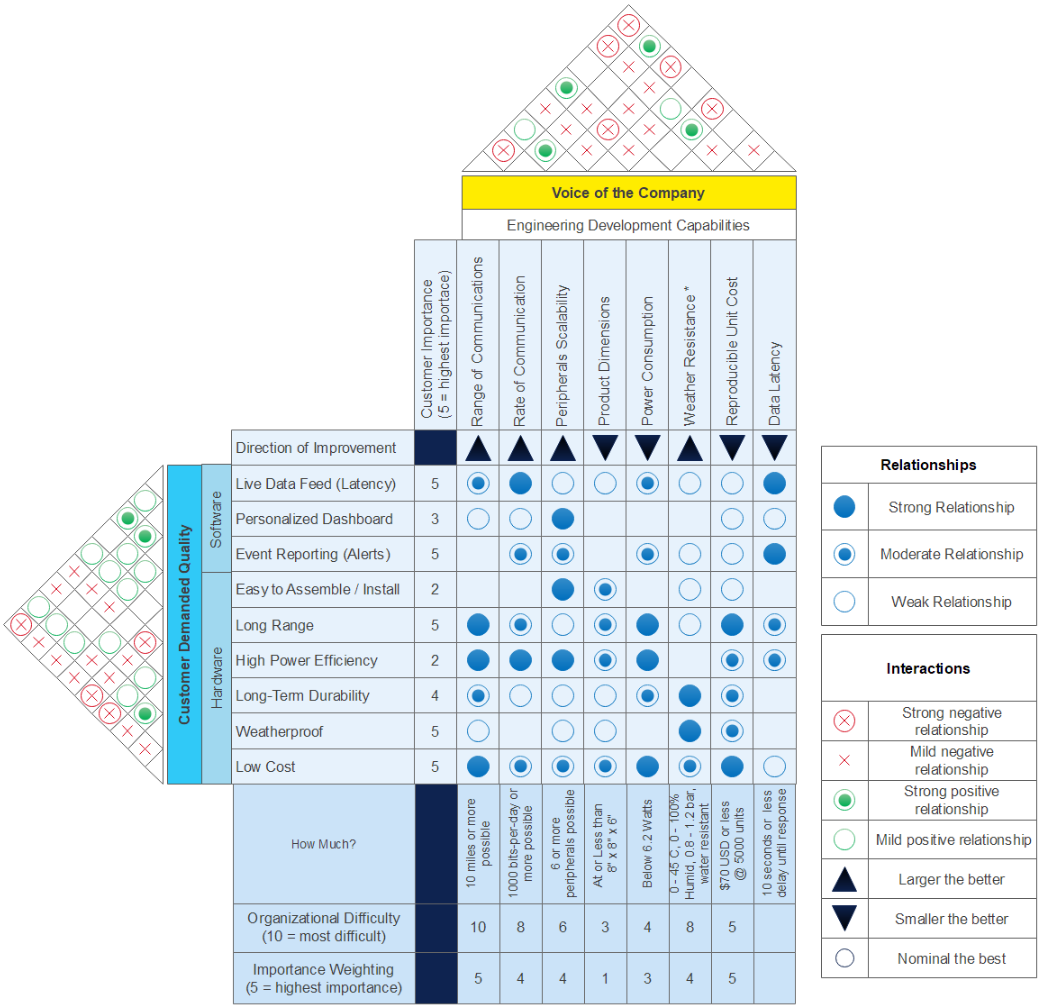



*Figure 0-2: House of Quality*

## Engineering Specifications

### *Range of Communications*

This defines a set distance by which a data-collecting device will be able to communicate with a network gateway. Given that bee-yards are usually placed within a mile of each other, 10 miles should be enough to maintain communication across yards. This allows the placement of network gateways at centralized locations to collect and deliver endpoint data to a remote server. The communication distance of 10 miles will be achieved by using a wireless transceiver capable of communicating using the Sub-1 GHz SIM bands. Current devices capable of operating across said bands can maintain a robust enough connection which is able to pierce walls and other forms of obstructions, even in the most urban environments. In contrast, hives are usual kept in rural environments with little obstructions other than trees, which has negligible impact on the range of a SUB-1 GHz signal. This should reinforce the possible range and robustness of the endpoint device. Additionally, while the range of communication is inversely corelated with response-time and cost, the data-rate may have the most significant impact on the range. As a result, a clever balancing act will be considered in selecting the data-rate.

### *Rate of Communication*

Because data-rate and range are inversely corelated, a larger communication range dictates that the signal could produce a significantly lower data throughput. As a result, a set data-rate must be defined to accommodate the expected traffic which may be transmitted. Both digital and analog sensor data are expected to be sent across the wireless network. In addition, endpoints incapable of communicating with a gateway may seek to delegate the transmission of their specific data to another endpoint which does have a connection. Correspondingly, the Implementations and Standards Section analyzes the required data that is to be recorded and estimates the rate of communication as presented in the illustration above.

### *Peripheral Scalability*

This declares the maximum number of external sensors which can be attached to a node. The node will be able to make such connections using a RS485 hardwired interface or wirelessly through Bluetooth. A maximum of 4 devices will be attachable over the hardwired interface while a maximum of 8 devices will be attachable over Bluetooth. While the limitation for the Bluetooth interface can be considered arbitrary, the limitation for the hardwire interface provides ease of communication and cable management when working with a hive. This will ease installation ease and hive access.

### *Product Dimension*

The project dimensions are dictated by the allowable area between a hive. It should also be discrete and attached enough to not be displaced if the hives are moved, by weather or by trespassers. We want the product dimensions to be close to nominal, but no larger than 8" x 8" x 6". This is also inversely related – a limiting factor – to the peripherals scalability, antenna size, weather resistance and power housing.

### *Power Consumption*

Although we are uncertain of the maximum power requirements at this time, we are limited by the cost and quality of power being supplied through solar panels which will be mounted to the top of the hive. The most power we can plausibly afford per unit, considering the cost of load cells and other included components per device, is 6.2 Watts of power supplied. Less power consumption is preferential because this will reduce the cost of per unit, reduce product dimensions, and allow more room for weather resistance measures, communications components. Reducing power consumption however, may also limit us in final peripherals scalability.

### *Weather Resistance*

The nature of the placement of the device on commercial beehives will require weather resistance. More weather resistance is better; increasing the weather resistance will also limit our area for communications components, power components, and of course peripheral scalability. The bare minimum of weather resistance should be able to protect the end-product from tropical summer to northern winter temperatures (0 – 45 degrees Celsius), low-to-high humidity 0 – 100%), heavy rain and snow, and weather depressions (0.9 to 1.1 bar of pressure). These should not be hard to accomplish. There are many national and international standards for our weather enclosures. Weather resistance enclosure standards are discussed further in the Standards section.

#### *Transmission Latency*

The response time ("Latency") of our online application, which will be accomplished via a website or app-store application, will need to be low. The lower the response time, the faster apiarists can see updates in their dashboard. We can feasibly accomplish a data latency of 10 seconds or less between updates to make the data appear as though it is "live". Device-level, this will depend upon a high rate of communication, and upon communications distance because this will need to be high enough that the server will pull the data from any yard. Latency is also negatively correlated with decreasing power consumption.

### Marketing Specifications

#### *Live Data Feed*

The latency of the data that we will be sending from our device to the user (apiarists) live must be low. As specified, it must be able to transmit every 10 seconds in order to maintain a live update status. This latency can be affected by the power and rate of communication, but also by proximity as it needs to work within the desired 10 miles along with a preferred, optimal data-rate.

#### *Personalized Dashboard*

A dashboard interface that will carry all important sub-fields that the user might want to have available. This will be a personalized tool that will not only list out the preferred and most important hive characteristics of the time, but it will also be updating to give a live feedback of every yard connected. This will also be where apiarists can receive and view push notifications that will be based from real time alerts gathered by the sensors of the device.

#### *Event Reporting*

These alerts are linked to and demonstrated in the personalized dashboard. Our device should have the capability of detecting any abnormalities that may be present using one of its many sensors. The alerts should be sent with as low a latency as possible and must be able to keep updating and informing the user of what the sensors are picking up. We expect to create a product that will warn things such as change in weight, detection of a certain unwanted chemical, disturbance from outside forces such as wild animals, etc.

#### *Ease of Assembly & Installation*

Our product will be one that will be easily accessible and usable by any user that has zero experience with electronic technology. Our model will consist of an easy to install main control unit, as well as easily attachable units to the sides of the hives that will only need to put around two cables with small sensors at the ends inside of the hives. Since the communication will be running through sub-1 GHz communication, then this will also make the device easily accessible when trying to add other sensors to collect more data.

### *Long-Range*

Our device is expected to cater to the needs of users that are trying to monitor their hives from far away distances. The distance of 10 miles is considered as appropriate proximity to be getting full information on the state of the hives at the fastest time possible. There is also the fact that these long distances are also remote areas where most signals do not reach and the user must be able to get all information…….

### *High Power-Efficiency*

Certain factors such as data rate/latency, distance, and maybe even sunny days all could affect power efficiency. The device will use the most optimal panels that will power a battery which will efficiently transmit power into the board. Since all power will be solar provided, the main expense for the user will be that of a battery which tend to last long for these models. To make the battery last longer, the power consumption can be reduced.

### *Weatherproof*

The user will need the device to work in regions where it will be exposed to the regular elements as well as extremities of the Florida region. The device will have to deal with cases such as hurricane winds, extreme heat, and wild animals such as bears. The casing it will come in should provide enough safety.

### *Low Cost*

This product should be as low cost to the consumer as possible and this will be made possible due to the easy integration and low-maintenance, expanding nature of the product, as well as its long-lasting power life-time through the combination of solar panels and low power batteries. The costs will be further reduced by having the base communications template and adding only necessary sensors suited to monitor each individual beehive.

## Proposed Verification Techniques

We are going to record video of the working functionality of the following engineering constraints: 10+ miles Range of Communication, 1000+ bits/day Rate of Communications, 6.2 Watts or less Power Consumption. Range of Communication will be demoed by showing GPS location of the hive transmitter and the cellular phone receiver and showing live data tracking being pushed at this range. Similarly, we can push as much data as possible at this range and record how much is pushed over a 24-hour period. We will measure the power consumption using a voltmeter at the input and ground of the communications device.

Weather resistance against the elements will be verified by submerging the weatherproofed device under 3 meters of water for 10 minutes, by leaving the weatherproofed device in the freezer for 10 minutes, by 10 minutes of 45 degrees Celsius in a scientific oven and then testing the working functionality of the electrical components of the communications device inside with a multimeter.

Within the Financials section we are also going to include a running tabulation of incurred costs, with receipts, and include at least three price quotes for 5,000 units of our communications device, in order to verify $70 USD or less unit cost at the quoted number of units.

We are going to verify, the day of the demonstration, the automated Mesh-Networking in close-proximity using ZigBee, Range of Communications and Data Acquisition, Data Latency, and Product Dimensions. Automated Mesh-Networking will be shown by bringing two bare-communications devices close together (within 10 feet) and showing within the application that they have "meshed" (grouped) into a single yard. Range of Communications and Data Acquisition will be shown through video-conferencing with a person next to a hive 10 or more miles away, showing that when he plays with the sensors in the hive, the informatics in the application change. Data Latency will be shown with a timer, that less than 10 seconds after he played with sensors, the informatics have changed ("Live Feed"). Product Dimensions (in enclosure) will be shown to be less than 8" x 8" x 6" using a standard 12" ruler.

Security of the transmissions can also be shown by presenting showcasing a sniffing example through the use of a software-defined radio receiver. This will simulate the attempt to achieve a man-in-the-middle attack on our communications end-product. They will not be able to decipher the data being transferred.

## Power Block Diagram

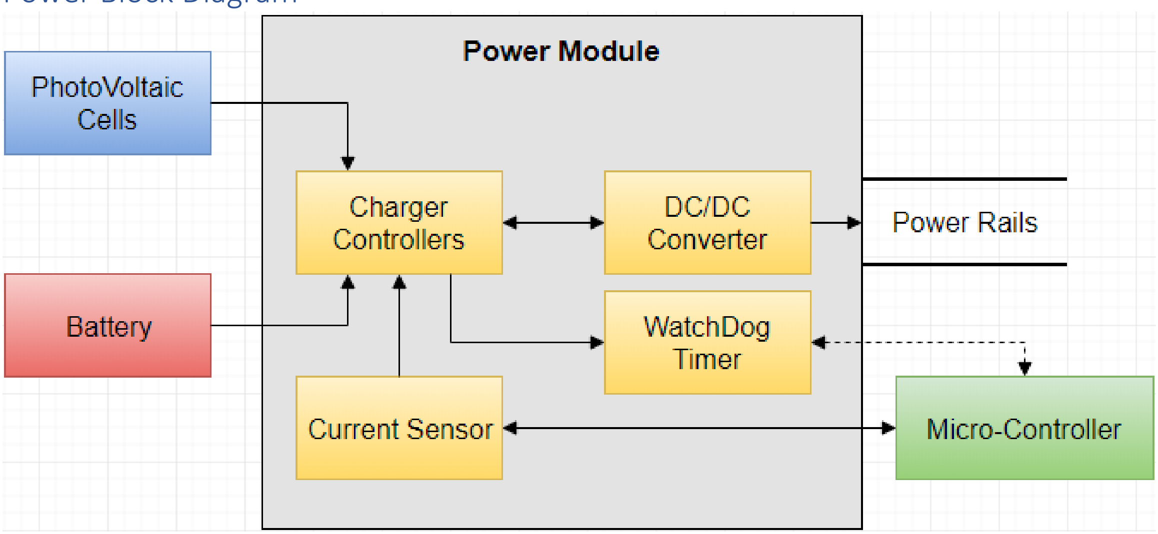



*Figure 0-3: Power Interface Block Diagram*

The Power Block Diagram figure above shows the power interfacing block diagram, illustrating how the Power Module helps the photovoltaic cells (PVCs) and specialized LiFePO4 battery to supply power to the Microcontroller Unit (MCU) and Power Rails to supply power to the peripherals (including sensors). The charge controller (trickle charger) will convert the PVC power to DC to charge the battery. The current sensor (controller) will output ultra-low current required for the MCU and the watchdog timer will ensure that software is terminated if it malfunctions, preventing erroneous looping. The DC/DC Converter will be used as a step-down converter in order to achieve 5 V and 3.3 V for various peripheral sensors.

## Hardware Block Diagram

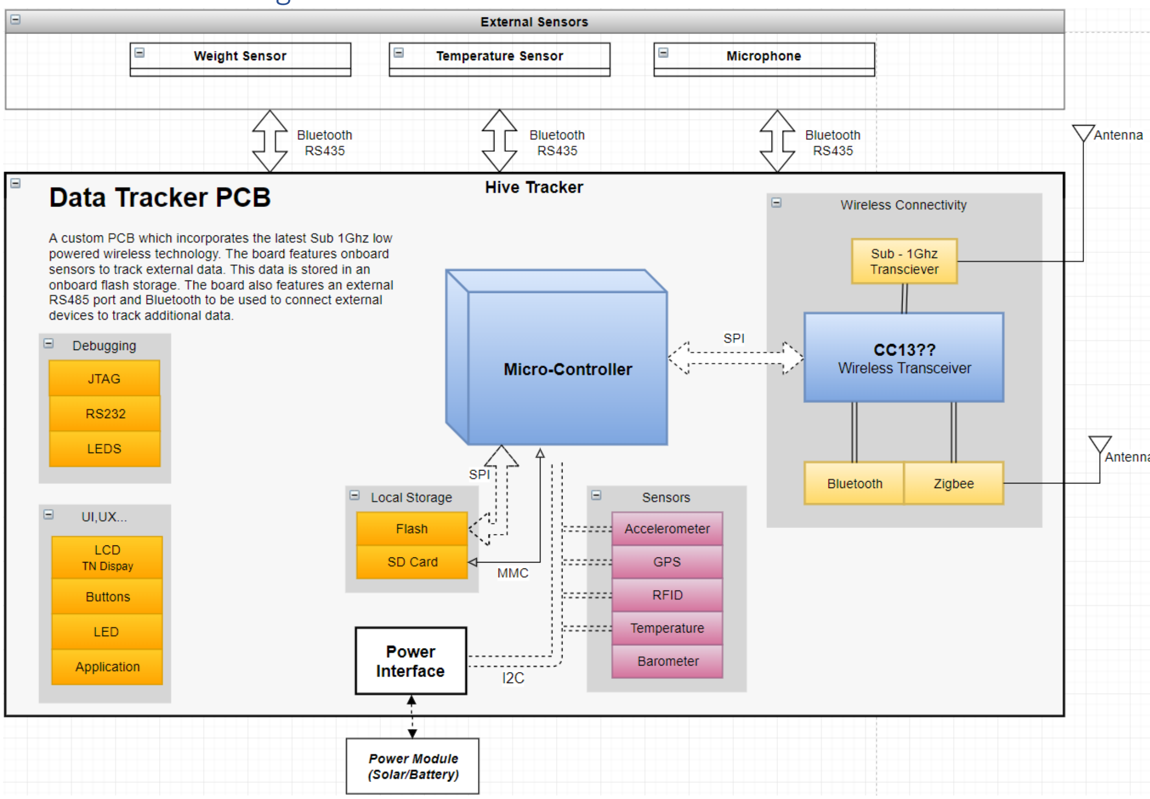



*Figure 0-4: Hardware Interfacing Block Diagram Including Hive Tracker and Peripheral Sensors*

The above diagram illustrates the target PCB design for the data-tracking unit. A standard Low Power Wide Area Network interface has not been selected as yet. The pros and cons of the current standards are being considered. While the LoRa stack does provide a viable method of deploying a custom network, their wireless transceivers are lacking key features such as Bluetooth connectivity.

Texas Instruments, on the other hand, does provide transceivers with built in microcontrollers and Bluetooth and also support various LPWAN protocols such as Sigfox. The listed sensors will be incorporated into the board along with an internal storage device. A debugging interface will be necessary for testing the ICs on the PCB. Although the standards for interfacing amongst the ICs have not been confirmed, modern chips do provide libraries which abstracts the low-level communication protocols. As a result, a widespread application could be developed and tested on a test board and ported fairly easy to an arbitrary development board. A method for generating user feedback using either LEDs or an LCD display is also being considered.

## Software Block Diagram

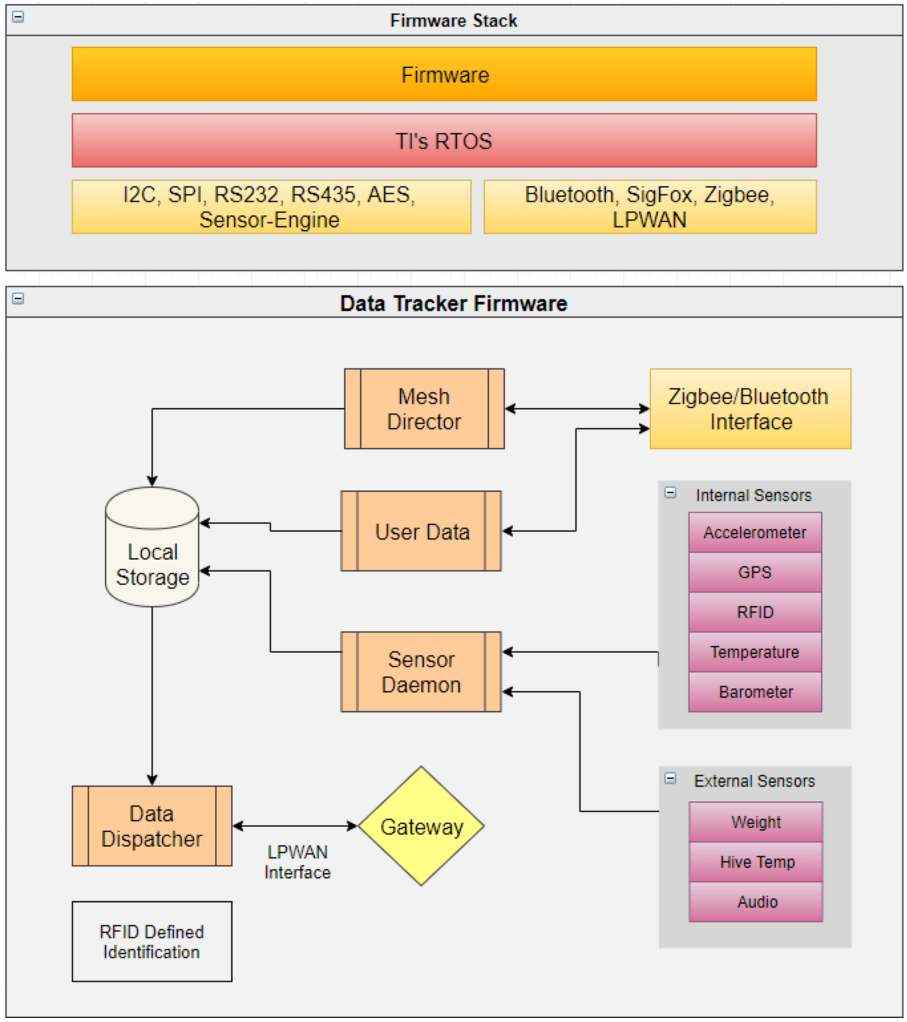



*Figure 0-5: Software Interface Including Firmware Stack and Embedded Data Tracker Firmware*

Texas Instrument provides a real-time operating system made specifically for IOT type devices. It employs various algorithms for reading and storing sensor data. Coupled with its Bluetooth and Zigbee interface, using Texas Instruments IOT platforms may ease the software development process. The firmware block diagram illustrated above describe the several types of tracked data. Internal sensors are those sensors internal to the tracking device (External to the hive). External sensors are those within the hive. The Bluetooth interface allows a user to connect to a hive using a phone, while the ZigBee interface allows that user to issue command to the entire yard at once. Data obtained from these data types are then dispatcher using the data dispatcher element to the gateway where it is translated to a TCP/IP packet and pushed to a web server.

# Research and Part Selection

This section includes an overview of current technologies associated with our project, within the scientific research community and those already available in market. We have included technical research into the best technologies to use – arrangements of parts – in order to realize our project end-goals. Also featured here is the parts selection, where we look at schematics for the technologies presented, and discuss which parts are unavailable, available, and choose the most ideal parts to fit our project constraints. The orders, sample request forms, and other information for these chosen parts are included in the Administration section later in this document. Further documents including datasheets may be included in the Appendix.

## Scientific Research

### Power

For this project we chose to power using photo voltaic solar panels in order to give the most durability to our device as well help reduce the overall cost for both market and engineering purposes. After much analyzing of different powering specifications and charge systems, we have decided to go with one that offers a connection from the solar panel straight to a battery that is then connected straight to our board. The battery charges when it's reached certain threshold level. This version is preferred to one that still utilizes the solar panel when the battery is full instead of always relying on the charge of battery because it requires less components and helps with the ease of build while still providing sufficient charge. In the regular market, solar panels for projects such as these go the same as for large-scale residential use: prices vary directly to both area and watts generated per area. For this project we found it convenient to use a small 6.2 Watt solar cell that will not should give us more than enough charge.

The device will have battery then be connected directly to the boards to power them and this powering shall have to be regulated according to the how much charge is in the battery as well as how much power is being supplied by the solar panel. The board will also need to step down the voltage from the battery to that of the PCB. In order to choose a decent controller, two main ones were looked at since they are compatible with our communication system: the TI BQ24210 and the BQ24650. The BQ24210 offers some great features such as Selectable Battery Tracking Mode to Maximize the Charge Rate from Solar Panel Using DPM Feature, and 20-V Input Rating, With Overvoltage Protection (OVP), 1% Battery Voltage Regulation Accuracy, Current Charge up to 800 mA with 10% Charge Current Accuracy, Thermal Regulation Protection for Output Current Control, and Low Battery Leakage Current. However, the BQ24650 offers a much higher current capacity, higher integration such as internal loop compensation, more safety features such as Battery Absent Detection and Thermal Shutdown, and MPPT capability which automatically helps get the maximum power point, at which the entire photovoltaic (PV) system operates with maximum efficiency and produces its maximum output power.

The charge at the regulation phases drops ensuring that a voltage is still present even when no current is available. This happens when the battery reaches below 1.2 Volts and needs to compensate the supply for its loss voltage. This system also protects the battery as any system such as this that lets its battery be completely depleted to 0 Volts will need to replace the battery.

## Networking Topologies

[TODO: compare and contrast several types of networks]

## Sensors Technology Applied to Honeybees

### *Weight*

Weight monitoring is one of the simpler hive monitoring techniques, however it also provides extensive data feedback throughout the year. Measuring the weight of a hive over time can show whether the hive honey output is progressing or declining. This can give valuable insight on the health of that specific hive. Smaller weight changes each day can show when the bees come and go from pollination, or if there are any abnormalities with their behavior in general. Not only can weight measurement give details about the bees in a hive, but it can also provide information on what type of plants the bees are pollinating and when they flower. This is all obtained by weighing each hive individually for an extensive period; when the weights are applied, they do not have to be operated from that point onward, meaning they are very easy to maintain.

### *Temperature & Humidity*

Honey Bees prefer a certain amount of humidity in the hive; there is consistent data to support honey bees preferring around 45%-55% humidity within the offspring nest of the hive. A humidity monitor can accurately reflect how close the humidity percentage of the hive is to ideal values. Bees also prefer certain temperatures as well; combining humidity and temperature data with weight data can accurately project how well a hive is doing and whether these conditions are affecting the health of the hive.

### *Lumens*

Light sensors can help accurately predict the length of a day as well as the weather conditions of each day. Knowing whether a day is cloudy or extremely bright is important because of the way honey bees can be affected. The cycles that are produces each year from the length of time the sun is up, as well as seasonal weather, can help predict how the honey bees will act during these conditions. This information can also help apiarists know when they specifically want to go out to the hives for maintenance.

### *Rain Gauges*

Rain gauges are another important aspect of hive measurement. Pollination USA has specifically requested a rain gauge device from Plan Bee. Rain gauges can give accurate measurements on the amount of rain that has fallen in a specific area. A heavy rainstorm will provide bees with less time for pollination, as most bees will seek cover inside of the hive. Knowing whether rain is a reason for abnormal foraging patterns is significant. Rain can also increase flowering, which may lead to an increase in pollination. Apiarists also need to maintain the hives and make sure that they are not flooded with rain water; knowing how much rain has fallen will help determine if the hive is having any technical problems worth monitoring further.

### *Video Recording*

Video Camera Streaming of yards can be useful for monitoring theft, as well as pollination patterns of the bees. Any abnormal activity could also be viewed from these cameras and uploaded to the customers device from the gateway. Pollination USA has asked for some sort of visual production device, whether that is a camera that takes a picture or short video during certain time intervals, or a constant video stream.

### *Census & Counters*

Bee counters can provide data on when bees enter and leave the hive. Knowing how many bees are in the hive can provide intel on pollination times and routes, as well as how well the hive is doing based on the number of bees counted in a specific hive and compared to a baseline of an average healthy hive count. Restricting the bees entrance and exit to one specific and rather narrow point may be necessary, but this would not affect the bees themselves if applied correctly. Video footage could even be added to bee counters so that more information can be obtained about what type of bees are entering and leaving, as well as if the bees exhibit specific behaviors, such as swarming.

### *Accelerometers*

Collected data on the specific vibrations of a hive could provide invaluable information. Bees exhibit certain vibration behaviors depending on the condition they are in. Recording these vibrations over time and comparing them to the health of the hive could provide accurate date on what vibrations of a healthy hive sound like. This data would not only be helpful for apiarists but would provide research information as well.

### *In-Hive Microphones*

Another great research technique would be in-hive microphones. Knowing how the hive sounds year round, especially when unable to open the hive and see the bees (such as in winter or during other intense whether patterns, like hurricanes) , would bring certainty to how well the hive is surviving. Building a portfolio of bee communication techniques would also provide information on the different ways bees communicate, and what specific sounds mean.

### *ASM Pheromone Sensors*

Pheromone sensors can give intel on mating inside of a hive, as well as if any predators are moving in on the bees, such as mites. This could prevent hive loss and spreading of invasive mites, as well as provide information on how well the hive is producing more bees.

## Technical Research

### Cloud Computing & Web Servers

There are several available options for cloud computing and web servers, Amazon Web Services (AWS), IBM Watson, Microsoft Azure, Google Cloud and Salesforce Watson. The TI CC1352R RF communications chip uses SigFox and limits us to AWS and IBM Watson for web services as our cloud computing base and web server. These two offer somewhat similar capabilities around flexible computing power, storage and networking, as well as the addon of machine-learning and artificial intelligence processing available. To compare the two, we have implemented a table below.

| | Cloud Computing Services | Amazon AWS | IBM Cloud & Watson |
|---|---|---|---|
| Pricing | Type of Discount | Reserved Instances (RIs) | Monthly Pricing |
| | Length of Commitment Required | 1 or 3 years | Monthly Commitment |
| | Range of Discount | Up to 75% | Up to 10% |
| | Other Documented Programs | RI volume discounts, Spot instances | Negotiated |
| Technical | Technical Approach & Documentation | Excellent | Very Good |
| | Service Level Agreements | Very Good | Satisfactory |
| | Management Approach | Satisfactory | Very Good |
| Performance | Past Performance / Uptime (Confidence) | High | Moderate |
| | Security | Excellent | Excellent |
| Offered Services | Computing | Yes | Yes |
| | Artificial Intelligence & Machine Learning Ability | Satisfactory | Excellent |
| | Storage | Yes | Yes |
| | Web Hosting | Yes | No |
| | Databases | Yes | Yes |
| | Networking & Content Delivery | Yes | Yes |
| | Migration | Yes | Yes |
| | Developer Tools | Yes | Yes |
| | Management Tools | Yes | Yes |
| | Media Services | Yes | No |
| | Security, Identity & Compliance | Yes | Yes |
| | Analytics | Yes | Yes |
| | Mobile | Yes | Yes |
| | AR & VR | Yes | No |
| | Application Integration | Yes | Yes |
| | Customer Engagement Tracking | Yes | Yes |
| | Business Productivity Tracking | Yes | Yes |
| | Desktop App Streaming | Yes | No |

| | | |
|---|---|---|
| Internet of Things | Yes | Somewhat – only Watson is supported for IoT applications |
| Game Development | Yes | No |
| Cost Management | Yes | No |
| Marketplace Software | Yes | No |

The yellow highlights support what we would like to make use of from their offered services, whereas the green highlights fundamentals, or bare necessities. IoT Applications MUST absolutely be supported for packet delivery and web hosting. This is not the case for IBM Cloud – only Watson is usable for IoT applications – so we decidedly be using Amazon AWS as our web server, web application hosting and for APIs. This is because of the ease of use and integration with Texas Instruments, and low relative cost compared to IBM Cloud. Although there is a time commitment required, the first year is free in our case, and our customer will likely not want to migrate cloud computing servers because new development and associated costs will be required. We may or may not add IBM Watson services as well, specifically for better machine learning architectures and performance.

### *REST – Representational State Transfer*

REST is a type of architecture for creating web services using standards and technologies that have already been developed, such as HTTP. REST does not require the customer to know that it is running or being used. This way, the customer doesn't need to know about the server and the resources on that server ahead of time. Anyone familiar with HTTP will have ease of use with REST, which is a greatly beneficial feature. Any coding language can be used with REST as well, adding to its adaptability with various consumers. REST is often compared to SOAP, which is another competing style of architecture.

## Frameworks

### *Frontend*

There are many available frontend frameworks for web development, based upon the three frontend languages we talked about in Standards: HTML5, CSS3 and JavaScript. We will need one of these frameworks for adding formatted and styled content, pages and animations to our web-based application. There are only a few really good development frameworks that are modular enough to get the job done, though, and of these we are tasked with deciding which will be the least complex, and modular enough to fit our web application specific needs. The table below compares the complexity and modularity of these different frontend frameworks, as well as other tangible items so we can make the best decision on a frontend web-app framework.

| Frontend Frameworks | Bootstrap | Foundation | Semantic UI | Pure | UIkit |
|---|---|---|---|---|---|
| Creator/Publisher | Mark Otto, Jacob Thronton | ZURB | Jack Lukic | Yahoo | YOOtheme |

| | | | | | |
|---|---|---|---|---|---|
| Released | 2011 | 2011 | 2013 | 2013 | 2013 |
| Current Version | 4.0 | 6.0 | 2.2 | 1.0.0 | 3.0.0 |
| Popularity (stars on GitHub) | 121,374 | 29,956 | 39,364 | 18,183 | 11,604 |
| Description | Sleek, Intuitive, Powerful... for faster and easier web development | The most advanced and responsive in the world | UI components based on useful principles from natural language | set of small responsive CSS modules | light, modular for developing faster and powerful websites |
| Core Concepts/Principles | RWD and mobile-first | RWD, mobile-first, semantic | Semantic, tag ambivalence, responsive | SMACSS, minimalism | RWD, mobile first |
| Framework Size | 578KB (minified and zipped) | 197.5KB (zipped) | 806KB (zipped) | 3.8KB (minified and gzipped) | 326.9KB (zipped) |
| Preprocessors | Sass | Sass | Less | None | Less, Sass |
| Responsiveness | Yes | Yes | Yes | Yes | Yes |
| Modular | Yes | Yes | Yes | Yes | Yes |
| Starting Templates/Layouts | Yes | Yes | Yes, very basic though | Yes | Yes |
| Icon Set | Not included | Foundation Icon Fonts | Font Awesome | None, Font Awesome usable | SVG icon system, library for outlines |
| Extras/Addons | None bundled, but many third-party plugins | Yes | None | None | Yes |
| Unique Components | Jumbotron, Card | Icon Bar, Clearing Lightbox, Flex Video, Joyride, Pricing Tables | Divider, Flag, Rail, Reveal, Step, Advertisement, Card, Feed, Item, | None | Article, Flex, Cover, HTML Editor embed |

| | | | | | |
|---|---|---|---|---|---|
| | | | Statistic, Dimmer, Rating, Shape | | |
| **Documentation** | Excellent | Good, many additional resources available | Very good, well organized and separate website guides through implementation | Good, but basic | Good, but basic |
| **Customization** | Options for seperate files for grid system and reboot, easy customization with Sass, no online customizer | Basic GUI customizer | No GUI customizer, only manual customization | Bsic GUI Skin Builder (online) | Advanced GUI Customizer available |
| **Browser Support** | Latest, All | Latest, All | Latest, All | Latest, All | Latest, All |
| **Licensed by** | MIT | MIT | MIT | Yahoo! Inc. BSD | MIT |

Of these, we will likely be using Bootstrap 4.0 because it has the best documentation of all of these frontend frameworks, and offers greater customization options, although not necessarily as accessible as the other frameworks. As well, the mobile-first and minimalism of BS4 offer better accessibility as an actual handheld application, which will work better for our apiarists for which we are creating this end-product to begin with.

It is also worth noting that Angular.JS will also be used. Angular JS allows the rending of website directly in the web browser during development, was developed and is published by Google. Frameworks can be either JS-based, or CSS-based, and the frameworks discussed above are all CSS-based, or a combination of the two. BS4 uses JQuery (a JS library) to add dynamic functionality to its web elements and can be used with Angular.JS. Angular.JS really allows for enhancement of HTML and adding more complex functionality and customization than BS4 alone offers.

### *Backend*

Because we have chosen to use Amazon AWS webserver services, the backend of our web applications will all be API driven. Any framework we use will be decided by the AWS server necessities, APIs and operating systems that power the web application's frontend.

Backend frameworks here are libraries of server-side programming languages that construct the backend structure of the website. The software stack comprises of database, server-side (backend) frameworks, the AWS server and the operating system (OS). We have a few options for backend frameworks:

| Server-side Frameworks | Ruby On Rails | ASP.NET | Django | Express JS | Golang (Go) |
|---|---|---|---|---|---|
| **Description** | 10x faster than JS or Java based frameworks, and easiest to use web framework, according to website | open source framework for modern web app services that are fast, simple and scalable | "pluggability" for easy creation for complex implementation; don't have to repeat yourself | light web application framework to help organize into MVC framework and use any templating language | object oriented, but not in the usual way; simple pieces connected by small interfaces |
| **Language** | Ruby | .Net languages | Python | Javascript | Go, gc assem, C++ |
| **Express Builds** | single, multi and hybrid | single, multi and hybrid | single, multi and hybrid | single, multi and hybrid | single, hybrid |
| **API Supported** | Yes | Yes | Yes | Yes | Yes |
| **Templating Engines** | Yes | Yes | Yes | Jade and EJS | Yes |
| **MVC Pattern** | Movel-View-Controller architecture | Model-View-Controller architecture | Model-View-Controller architecture | Model-View-Controller architecture | Multi-paradigm, procedural object-oriented, concurrent |
| **Platform** | None | .Net | None | Node.JS | None |
| **Operating System (OS)** | Cross-Platform | Microsoft Windows, Linux (limited support) | Cross-Platform | Cross-platform | Cross-platform |

| | | | | | |
|---|---|---|---|---|---|
| **Unique Components** | Ajax functionality | No | Ports to other languages | Express Generator (automatic) | Go language |
| **Documentation** | Excellent | Good, but online expertise available | Excellent | Good, but several tutorials available | Excellent, with added templates and videos |
| **Size** | 2.9 MB | 4MB | 7.6MB | 2.8MB | Compiles to binary, very small |
| **Stable Version** | 5.2.0 | 4.7.1 | 2.0.7 | 4.16.3 | 1.10.3 |
| **Stable Date** | 2018 | 2017 | 2018 | 2018 | 2018 |
| **Initial Release Date** | 2005 | 2002 | 2005 | 2010 | 2009 |
| **Creator / Publisher** | David Heinemeier Hansson | Microsoft | Adrian Holovaty, Simon Willison | T.J Holowaychuk | Robert Griesemer, Rob Pike, Ken Thompson |
| **License** | MIT | Apache 2.0 | Django Software Foundation (DSF) | MIT | Google |
| **AWS Supported** | Yes | Yes | Yes | Yes | Yes |

We will be using Golang in combination with SQL language. We have chosen Golang because it is significantly faster than other backend frameworks and dependent upon usage and not package size, and because it is more regularly updated and directly supported by Amazon AWS. As well, it allows for faster development, which is exactly what we need in a time crunch, and runs directly on Google development environments, which we will be using as they are free, as well.

## Firmware

### *FreeTOS – Free Real-Time Operation System*

FreeTOS is a real-time operating system developed for embedded devices. It was designed ot be as simple as possible; the kernel only relies on 3 C files. Like TI-RTOS, FreeTOS features a small memory footprint and support scheduling, thread priority, dynamic memory allocation, static memory allocation, and semaphores and other memory management units. FreeTOS provides rapid application development and also a robust enough framework to maximize application portability and extensibility.

While Texas Instruments' RTOS is based on FreeTOS, TI-RTOS also boasts additional features which severely decreases development time and aid in testing and deployment. The unfortunate decision to relegate TI-RTOS to Texas instrument designed devices severely limits application portability and even upgradability. Because of the time constraints allotted to complete this project we'd decided to use Texas Instrument development environment to increase application development time. Such a solution would allow us to fully integrate wireless and wired communication methods with ease. Texas Instrument's also provides from a significant amount of integrated devices which are fully supported and across their many software tools and integration layer.

### *Data-Tracker Firmware*

TI-RTOS – Real-Time Operating System

Texas Instruments provides a low-level real-time operating system deliberately called RTOS, or real-time operating system. This framework contains a micro-kernel, along with drivers, middleware and a hardware abstraction layer (HAL). These components provide an approachable programming interface which abstracts the application software from the underlying hardware. This promotes portability and usability as code will be allowed to be used across a diverse set of microcontrollers. TI-RTOS. was written in C and exposes 90% of the features available for the micro-controller. This significantly accelerates application development while also shielding the developer from the assemble interface. Texas Instrument also provides the full source code to the public and does not require a runtime license fees. Texas Instruments also furnishes a vibrant community, with active Texas Instrument employees offering costumer support and advice.

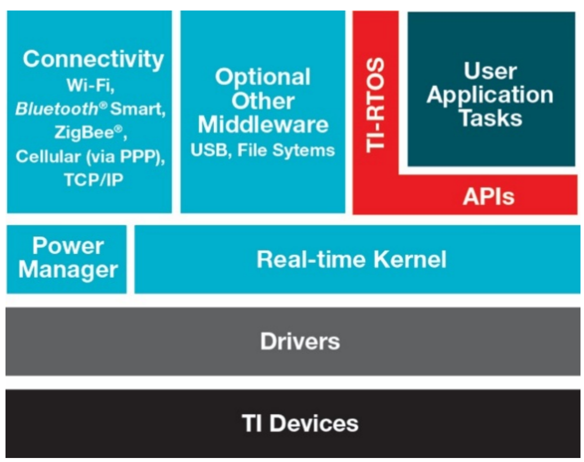



*Figure 0-1: TI-RTOS User Application Stack*

TI-RTOS provides a deterministic micro-kernel which dictates that kernel code should be executed within a pre-determined period of time. This minimizes time spent within the kernel code and allows application code to be executed more actively: as a real-time operating system should. The kernel also offers preemptive multi-threading and synchronization services. Such service allows application developers to employ multithreaded application with the valid tools needed to manage resource sharing and processing scheduling. TI-RTOS also offer device drivers which are able to initialize various micro-controller features such as UART, $I^2C$ and ethernet. These drivers provide an approachable application-programming-interface for interacting with said devices and managing device resources. (Texas Instrument, n.d.)

TI-RTOS is also integrated with Texas Instrument wireless connectivity stack, provided by Texas Instrument's wireless transceivers boasting Simplelink capabilities. This feature includes Wi-Fi, Bluetooth, Zigbee, and Texas Instrument's Sub Ghz network solutions. Additionally, TI-RTOS offers a comprehensive set of power saving features which permits application developers to leverage underlying hardware capabilities of their chosen microcontroller. (Texas Instrument, n.d.)

TI-RTOS provides an extensive list of features and capabilities which eases application development for Texas Instrument micro-controllers. To increase application efficiency, Texas Instruments RTOS was written in a modular manner, whereby unnecessary features could be omitted from the final application build. This permits developers to further stretch the limited resources available on such restrictive platforms.  We have made a table comparing RTOS below.

| **RTOS** | | **TI RTOS**<br>by TI | **ARMRTX**<br>by Keil | **FreeRTOS**<br>by Real Time Engineers Ltd. | **Micrium**<br>by Micrium |
|---|---|---|---|---|---|
| Scheduler Type | | Pre-emptive | Round-robin (default), Pre-emptive, Cooperative | Pre-emptive, Cooperative | Pre-emptive |
| CMSIS Compliant | | No | Yes | No | No |
| Services | Type I | Tasks, SWIs, HWIs, Software Timers | Tasks, SWIs, Software Timers | Tasks, Co-Routines (task share stack), Direct TASK notifications | Tasks, Software Timers |
| | Type II | Semaphores, Mutex, Mailbox, Events | Semaphores, Mutex, Mailbox, Events | Software Timers, Semaphores, Mutex, Events | Semaphores, Mutex, Mailbox, Events |
| Interrupt Latency | | Zero latency interrupts supported (115 cycles for ISRs with TI-RTOS calls) | Zero latency interrupts supported | Zero-latency interrupts supported | Unknown |
| Device-Specific Support | | Systick, Interrupts, Exception Handling | Systick | Systick | Systick |
| Device Drivers | | SPI, SPI-SD, | None | None | None |

| | | | | |
|---|---|---|---|---|
| | $I^2C$, UART, Timer, RTC, Timestamp, Watchdog | | | |
| **Flash Size** | 4K to 10K | Less than 4K | 5K to 10K | |
| **Low Power Support** | Tick Suppression, Device-specific Power Manager | Tick Suppression, Device-specific support coming soon | Tick Suppression, Pre- and Post-sleep macros for customization, Idle task hook | Idle task hook, Tick suppression coming soon |

## Communications Technologies

### *LPWAN – Low Powered Wide-Area-Network*

The project specifications require that the data collecting device be able to communicate with a user deployed access point at a minimum of 10 miles, while also maintaining cost effectiveness and power efficiency. Standards such as Bluetooth and Wi-Fi are incapable of communicating at the necessary range, while cellular standards require significant cost and limited coverage. This has led to an emerging market segment whereby low bandwidth devices are developed to communicate across very large distances using cost effective subscription models.

Emerging standards are being promoted to meet the growing demand for such device. Since the varying market segments, require different marketing specification and consideration, each standard should be meticulously examined for their advantages and disadvantages. As a result, this section seeks to decipher the best solution, which would supply the most robust and reliable connection while meeting the technical requirement set forth by this project. Listed below are the leading long range wide area network standards currently being deployed to satisfy the growing LPWA demand.

### Weightless

A proprietary wireless solution with open hardware and software stacks. It relies on a central gateway device to manage 1000s of connected devices. The primary factor differentiating such standard from the others is the wireless baseband used for communication. Weightless proposes using the wavelength radio transmission of unoccupied television band. Weightless also proposes AES encrypted end-to-end communication and guaranteed security and anonymity (Weightless, n.d.).

### NB-IoT – Narrow-Band Internet-of-Things

This is a Low Powered Wide Area Network standard being developed by 3GPP; an organization with oversight over similar wireless cellular technology such as GSM, UMTS, and LTE. NB-IoT relies on a subset of the finalized LTE standard with a focus on low-cost, long range indoor coverage with high connectivity density. It operates on a single narrow band of 200 KHz and uses Orthogonal Frequency-Division Multiplexing (OFDM) for its downlink communication and Single Carrier Frequency-Division Multiple Access for uplink communication (OFDMA). (Huawei, n.d.)

### SigFox

Currently the leading Low Powered Wide Area Network provider. Sigfox employs a proprietary wireless stack which runs on the Industrial, Scientific, and Medical ISM bands. It relies on thousands of carrier-deployed gateway devices, scattered across multiple contents; Sigfox professes it has accomplished “global coverage,” but such claim has been regulated to urban environments. Sigfox, inherently is a low-cost subscription service whereby connected devices are meant to transmit small sets of data, on the order of 100s of bits per day. Sigfox subscriptions also run at about 1 dollar per year per device.

### LoRaWAN – Long-Range Wide-Area-Network

An open-sourced low powered wide area networking stack designed to provide long range communication between device and gateway. While there are commercial providers expanding coverage by deploying gateway devices across the content, private users are also able to deploy their own gateways and avoid recurring subscription costs. Where the LoRa stack shines is in its open-sourced protocols and implementation details. LoRa Gateways could be created with off-the-shelf parts and deployed anywhere and maintain a significant range. This is accomplished by utilizing the Sub-1 GHz ISM bands. Additionally, LoRa relies on a chirp spread spectrum modulation scheme for both uplink and downlink connections to provide expanded range and reliability. This is all accomplished by wireless transceivers, provide by Semtech, the company behind the LoRa standard.

### RPMA - Random Phase Multiple Access

This is a proprietary Low Powered Wide Area Network stack developed by Ingenu. RPMA relies on the ubiquitous 2.4 GHz ISM bands but is able to prove significant coverage using minimal access points. Using high gain antennas, Ingenu show that a single access point has the capability of hosting approximately 400,000 devices and is also capable of covering as much as 30 square miles. A down-side of this technology is cost, while not advertised, Ingenu seeks to market their hardware to large enterprises, and also restricts private network deployment (RPMA access points are only rented to organizations within areas poised for coverage).

### Texas Instrument SimpleLink

Texas instruments Low Powered Wide Area Network solution, which relies on the Sub-1 GHz ISM band. Unlike similar technologies, Texas Instruments utilizes narrowband channels, relling on less than 25 KHz, which has shown to strengthen signal co-existence performance in highly congested areas. In addition, Texas Instruments utilizes Gaussian Frequency-Shift Keying modulation to greatly extend the range of communication. The entire networking stack, is also open sourced, allowing users to deploy their very own private network without additional costs. Texas Instrument also offer a wide range of microcontrollers with integrated SimpleLink transceivers. These system-on-a-chip solutions also feature additional wireless standards such as SigFox, Low Powered

Bluetooth, and WiFi. Texas Instruments retains the record for the furthest LPWAN transmission, at over 90 kilometers.

| Name of Standard | LTE-Cat M | SigFox | LoRaWAN | Ingenu RPMA |
|---|---|---|---|---|
| Frequency Band | Cellular | 868/902 MHz ISM bands | 433/868/780/915 MHz ISM bands | 2.4 GHz ISM bands |
| Channel Width | 1.4 MHz | Ultra-narrow band | 64x125 KHz, Modulation: Chirp Spread Spectrum (USA) | 1 MHz (40 channels available) |
| Range | 2-5 km urban | 30-50 km rural, 10 km urban, 1000 km LoS | 10 km rural, 2-5 km urban | greater than 500 km LoS |
| End Node Transmit Power | 100 mW | 10 uW to 100 mW | less than 27 dBm (USA) | up to 20 dBm |
| Packet Size | Defined by User | 10 bytes | 12 bytes | Flexible 6 B to 10 kB |
| Uplink Data Rate | Around 200 kbps | 100-140 bps | 900-100 kbps (USA) | Up to 624 kbps |
| Download Data Rate | Around 200 kbps | Max 4 messages of 8 bytes/day | 900-100 kbps (USA) | Up to 156 kbits |
| Devices per Access Point | 20k+ | 1M | 100k uplink, 1M download | 364k |
| Topology | Star | Star on Star | Star | Star supported with an RPMA extender |
| End Node Roaming Allowed | Yes | Yes | Yes | Yes |
| Governing Standard Body | 3GP | SigFox | LoRa Alliance | Ingenu (formely OnRamp) |
| Status | 13 Released June 2016, In Deployment | In Deployment | Spec released June 2015, In Deployment | In Deployment |
| Implementation Costs | High | Low | Low | High |
| Recurring Costs | Medium | Medium | Low | High |

The table above compares the major Low Power Wide Area Network technologies. To adhere to the cost constraints presented in the requirement specifications, standards such as Ingenu's RPMA, and LTE-Cat M, which required significant upfront costs, were disregarded. Similarly, closed-source services which relied on provider coverage, such as SigFox were also disregarded for their restrictive outlook towards privately deployed networks. Weightless and nWave are currently have not significant market penetration, and as a result, have limited wireless transceiver options or community created devices. This decision has relegated our final decision to either LoRa and Texas Instrument's SimpleLink.

### *LoRaWAN – Long-Range Radio Wide-Area-Network*

Just 4 years ago, the word LPWAN was not even listed as a word; it is now a buzz-word in a rapidly growing market segment. The Internet of Things has gain tremendous backing and is proposed to continue its exponential increase within the coming years. While LoRaWAN is purported to have significant market share in the LPWAN space, its primary communication methods do present sever restrictions. LORA relies on the chirp spread spectrum modulation technique. Invented in 1933, this modulation technique is rarely used or for communication because of its co-existence limitation. Such limitation restricts data transfer rate of LoRa devices to 18 bits-per-second. At such speeds, a 30-byte message would take 2 minutes to transmit across a LoRa network. This greatly restricts data throughput and resiliency. In contrast, Texas Instrument implements a narrowband communication method for their simple link long range wireless communication. Such modulation technique can drive up to 1.2 kilobits per second and also offers significant better co-existent performance. Because of such research, we've decided to use Texas Instrument's Low Power Long Range solution to drive our communication stack. Texas instrument also provides additional tools and supporting documents which will aid in implementing such a communication stack.

## Parts Selection

This is the most important subsection within Research, where we will be deciding and finalizing the parts to be used in our final implementation. Three areas need to be covered for our application: power, communications and sensors. Power will include everything necessary for realization of the power block diagram presented in the Project Description section: voltage regulator, trickle charger, batteries, power IC for managing power storage, and solar panels.

Communications will include such things as necessary to realize the RF (or communications) portion and microcontroller of our design. This should include the following: antenna, antenna connectors (to PCB), GPS, RF switches, communications-specific chips (such as the TI CC1352R, and others), and flash memory chips for temporary data storage for transmission. It will also include many specialized resistors, capacitors, and inductors that we will need for power output management and filtering of RF components; this will be discussed further in the Implementation section.

The final part of Parts Selection will include sensors for everything we discussed implementing with Steven Eisele. This will include: temperature sensors (thermistors), internal measurement units (IMUs), pressure sensors (force transducers), light sensors (photodetectors), gyroscope, vibration sensors, humidity and moisture sensors, and a few others that will be further discussed within the Implementation section.

## Power

### *Trickle Chargers*

In order to utilize the photovoltaic cells to power our project, we will first run the solar panel's output voltage through a rechargeable battery that will then deliver the voltage gathered to the rest of the PCB. Certain parts of this battery system require control such as making the solar panels stop charging the battery when it is fully charged as well as measuring how much charge is left in the battery in order for the recharge cycle to be triggered to restart. For this former mentioned process it is important to have MPPT (Maximum Power Point Tracking) in order to regulate the current and voltage delivered so that the maximum ideal power is achieved.

| Chips | BQ24650RVAT by Texas Instruments | NCP1294EDBR2G by ON Semiconductors | LT3652IMSE#PBF-ND By Analog Devices, Inc. |
|---|---|---|---|
| Voltage Out (Max) | 28 V | 15 V | 32 V |
| Voltage Out (Min) | 5 V | 3.8 V | 4.95 V |
| Current Out (Max) | 10 A | 1 A | 2 A |
| MPPT Setting | Yes | Yes | Yes |
| Frequency-Switching | 600 kHz | 1 MHz | Unknown |
| Fault Protection | Current Limiting, Over Temperature, Over Voltage | Current Limiting, Over Temperature, Over Voltage | Over Temperature, Over Voltage |
| Operating Temperature | -40°C ~ 85°C | -40°C ~ 125°C | -40°C ~ 125°C |
| Control Features | Frequency Control, soft start, sync | Frequency Control, soft start, sync | Frequency Control, soft start, sync |
| Cost | $4.82 | $2.13 | $7.30 |

From our gathered options we have chosen the BQ24650RVAT for a range of reasons. The main reason for our choice was due to the voltage range per cost. The BQ24650RVAT delivers the most voltage for how cheap it is. It is also delivers higher power since it has a significantly higher output current compared to the other options.

### *Switching Programmable Voltage Regulator*

These IC's are used to step down the voltage from the rechargeable battery that is originally too high for the PCB. It provides a DC to DC transformation from the power that must be picked up at a moderate level from the solar panels to the much smaller values required to power our board effectively.

| Chips | MC33063ADR by Texas Instruments | NCP3064 by ON Semiconductors | MC34063ECD-TR by STMicroelectronics |
|---|---|---|---|
| Voltage In (Max) | 40 V | 40 V | 40 V |
| Voltage In (Min) | 3 V | 3 V | 3 V |
| Voltage Out (Max) | 38 V | 38 V | 38 V |
| Voltage Out (Min) | 1.25 V | 1.25 V | 1.25 V |
| Current Out (Max) | 1.5 A | 1.5 A | 1.5 A |
| No. Outputs | 1 | 1 | 1 |
| Frequency Switching | 100 kHz | 150 kHz | 100 kHz |
| Operating Temperature | -40°C ~ 85°C | 0°C ~ 70°C | 0°C ~ 70°C |
| Precision Internal Reference | 2% | 1.5% | 2% |
| Cost | $0.57 | $1.12 | $0.61 |

Though all options are very similar, the best choice for this project is the MC33063ADR since it carries a better set of specifications in terms of temperature control and frequency shifting. The higher the frequency shifting, the lower the efficiency which would be a negative tradeoff for this sort of project. Another reason why the MC33063ADR is the most ideal choice is due to its accessibility: It is considerably cheaper than the NCP3064, and the MC34063ECD-TR can only be bought in large quantities which also drive up the price beyond the ideal amount. It also has a higher range for operating temperature.

### *Batteries*

For the choice of battery, there are many types of rechargeable batteries that can be powered by solar cells. For the sake of both price and product size/dimensions, this project will use a small, sealed, lead acid battery. These are quite common and fit our standards appropriately. The specifications could be of a battery that of 6 Volts at around 4~8 Ampere*Hours.

### *Solar Panels*

| Panel | Semi flexible solar panel 10W by Crystal Solar | Medium 6V, 2W solar panel by Adafruit Industries LLC |
|---|---|---|
| Max Power | 10 W | 2 W |
| Max Voltage | 10 V | 6 V |

| | | |
|---|---|---|
| Connector | MC4 Compatible Connector | 3.5 mm OD/1.1 mm ID DC jack |
| Cost/Watt | $0.98 | $15 |

For the voltaic cells we have chosen are ones that have a peak power of 10 watts with 10 volts at around 1,000 amperes. The reason for these specific parameters is because an input of 10V at 1,000A, though small, fills the battery after a day of full charging so it can properly discharge at night. It also has a decent amount of output voltage and current in terms of what our control chip can handle. We have also chosen this model because it is far cheaper than the rest that are around these specifications.

## Communications

### *Antennas*

For RF applications, the importance of the antenna is the interface between radio waves propagating through space and electrical currents moving in metal conductors, used with a transmitter or receiver. The antenna radiates current as electromagnetic radiation (EM waves or radio waves). It also has the power to produce electrical current at its terminals from incoming reception. There are several types of antennas we could use for our specific application, including dipole antennas, directional antennas, patch and microstrip antennas (onboard), sector antennas, yagi antennas, parabolic and dish antennas, and grid antennas. The table below compares a few lower-cost choices we have for antennas that fit our specific application.

| Antennas | Duck Antenna RP-SMA by SparkFun | YA90011 Yagi Antenna by DMS Wireless | AU09G6HQ-NF Omni Antenna by Altelix |
|---|---|---|---|
| Operating Freq. (MHz) | 900 or 1800 | 900 | 824 to 960 |
| Output Power (dBi) | 2 | 11 | 6 |
| Range | Medium-to-Long | Very long | Long |
| Nominal Impedance (Ohm) | 50 | 50 | 50 |
| Type of Antenna | Directional (Duck) Antenna | Directional (Yagi) Antenna | Omni Directional Antenna |
| Standards | SigFox,<br>WiFi | Yagi,<br>SigFox,<br>WiFi | GSM 850/900 Cellular,<br>WCDMA,<br>SCADA,<br>LPWAN, LoRa,<br>LoRaWAN, RFID,<br>Multipoint and NLOS |

| | | | |
|---|---|---|---|
| Connector Type | RP-SMA Female | Wire-In | RP-SMA Female |
| ROHS Compliance | Yes | Unknown | Yes |
| FCC Compliance | Yes | Unknown | Yes |
| Price | $7.95 + shipping | $2.99 | $24.99 |

Duck, Yagi and Omni-Directional are the most applicable to our project. The YA90011 antenna is very powerful and very long range but has a very narrow usage band and dampens the signal outside of that, so it is likely not feasible for 2.4 GHz. The AU09G6HQ-NF Omni-Directional Antenna would be perfect for our gateway. It is also insulated and has full compliance with all standards we are using – most importantly GSM for cellular communications channels. As well, the output power gain is good and will deliver long range, as needed.

For all other implementations excluding the gateway, we may want to use the cheaper option of the RP-SMA Directional Duck Antenna. It will function reasonably well at 2.4 GHz which we need for Bluetooth 4.0 and ZigBee implementation. As well, it will function for wireless transmission of data to the gateway as needed. Power delivery and range are not as good as the AU09G6HQ-NF, and directionality is not ideal either; however, they do not need to be. All we need these smaller antennas for is delivery to the gateway, like a middleman between the sensors and long-range transmission.

We may also look at PCB-specific RF antennas, and JSC-type antennas, or create our own path or microstrip antennas for short-range ZigBee applications. These will come in Implementation, as needed.

### *Antenna Connectors*

Antenna connectors are likewise needed to connect the PCB to the antenna. There are a few standards for sizing of antenna connectors. The two types of antennas we purchased both used Reverse-Polarized SMA (RP-SMA) female connector types, as per FCC requirement for wireless PCBs in homes. However, we will not be in homes, so this requirement does not restrict us. And, as we may in future decide to go with a JSC-type antenna we have also included a JSC-type coaxial PCB connector by Murata. These are much smaller and less intrusive, but also lower range; as such, they may be used for ZigBee protocol short-range chips that we use within the "yards" and not necessarily for the Gateway.

| **Antenna Connectors** | **Reverse Polarized SMA Connector** by Sparkfun | **RP-SMA-J / RP-SMA-K Connector** by Areyourshop | **MM5829-2700RJ4 Coaxial Series Cable Connector** by Murata |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Supported Antenna | Reverse Polarized (RP) – SMA standard-following antennas | RP-SMA-J or RP-SMA-K standard following antennas | Coaxial JSC Type Connector |
| Connection Type | Female | Female | Female Plug |
| FCC Compliance | Yes | Unknown | Yes |
| Angle | 90° | 45° or 135° | 90° |
| Price | $1.95 + Shipping | $5.35 + Shipping | $0.63 |

We have already ordered the RP-SMA connector by SparkFun, because it is matched by manufacturer and connection type to our RP-SMA Duck Antenna that we also purchased from SparkFun. We still intend to use these for non-gateway applications. However, we have also ordered the MM5829-2700RJ4 Coaxial Series Cable Connectors from Murata, because they are used directly in the reference design for the Texas Instruments CC1352R transceiver chip and MCU. We may still choose to go with an JSC type connector, once we begin PCB-level implementation, if the duck antenna does not work as well as expected for ZigBee and Bluetooth transmission.

### *RF Switches*

Because we intend to use multiple channels, an RF switch is needed; a MUX cannot be used because of the high impedance, and digital signals will not be used. RF switches route high frequency signals through transmission paths by cleverly utilizing the signal frequency as the controller for output, in the same way the MUX uses binary logic for control. Because we will be using two frequencies for inputs and outputs, we will need a transfer switch for double pole, double throw (DPDT) which allows inputs from one channel and outputs to two channels, and likewise the reverse is true for signal intake.

| **Chips** | **PE4250** by Peregrin | **XMSSJE 3GOPA** by Murata | **BGS13S4N9** by Infineon |
|---|---|---|---|
| Operating Freq. | 0.1GHz-2.7GHz | 0.1GHz-2.7GHz | 0.1GHz to 3GHz |
| RF Impedance (Ohm) | ±50 | ±50 | ±50 |
| No. Inputs | 1 | 1 | 1 |
| No. Outputs | 2 | 2 | 3 |
| Bidirectional (Receiver/ Transceiver) | Yes | Yes | No |
| Temp. Op. Range | -40˚C ~ +85˚C | -40˚C ~ +85˚C | -40˚C ~ +80˚C |
| Price | $0.94/250 chips | $0.63/250 chips | $0.17/250 chips |
| Availability | Available | Out of Service | Available |

The reference schematic design provided by Texas Instruments utilizes a Murata XMSSJJ3GUP-054 to effectively deal with RF switching for the CC1352 dual-band chips.

The Murata XMSSJJ3GUP-054 routes the 900 MHz, and 2.4 GHz signals from the antenna to the Wireless Microcontroller Unit (WMCU). The chip and accompanying documentation could not be found.

A suitable replacement was found, which worked at the same frequencies and provided similar impedances. Peregrin's PE4250 operates at an equal operating frequency, requires similar input voltage and also incorporates an internal DC blocking capacitor. This removes the need for the DC blocking capacitor, C36, from the 900 MHz band, reducing overall unit cost and additional parts required. In addition, Peregrine's PE4250 is also well affordable, and is also well documented with included reference designs.

### *Communications Chips (MCU + Wireless Transceiver)*

The MCU and Wireless transceiver integrated Communications Chip is arguably the most important chip for our Internet-of-Things Sub-1GHz Communications Template project. There are few options for long-range sub-1GHz communications transceiver chips that support IP.

| Chips | | CC1352R by TI | CC1352P by TI | SX1276 by Semtech | S2-LP by STM |
|---|---|---|---|---|---|
| Description | | Support for Sub-1GHz + 2.4 GHz concurrently with the lowest power multi-band wireless MCU | Support for Sub-1GHz + 2.4 GHz concurrently with an integrated 20dBm PA enabling much longer range | RF transceiver/modem that provides ultra-long range spectrum | ultra-low power low data-rate transceiver, suitable for ISM bands and Wireless M-Bus |
| Cost | | $6.85 | Unknown | $6.17 | $3.63 |
| Availability | | Available | Available in August | Available | Available |
| Implementation Documentation | | Excellent | Excellent | Satisfactory | Good |
| Key Features | SimpleLink MCU Platform Compliant | Yes | Yes | No | No |
| | Application MCU | ARM Cortex M4F | ARM Cortex M4F | None | STM32 Nucleo |
| | Memory | 352kB Flash, 256kB ROM, 80kB RAM | 352kB Flash, 256kB ROM, 80kB RAM | None | 128kB Flash, 64kB ROM, 16kB RAM |

| | | | | |
|---|---|---|---|---|
| Standby Current Consumption | 0.8µA | 0.8µA | 9.9 mA | 7 mA |
| Output Power | 5 dBm | 20 dBm | 14 dBm | 16 dBm |
| Communication Bands Supported | Sub-1GHz, 2.4GHz concurrently | Sub-1GHz, 2.4GHz concurrently | 137 MHz to 1020 MHz | 413-497MHz, 452-527MHz, 826-958MHz, 904-1055MHz |
| Communications Technologies Supported | Bluetooth + Zigbee, Sub-1GHz, Wi-Fi, Multi-Standard | Bluetooth + Zigbee, Sub-1GHz, Wi-Fi, Multi-Standard | LoRaWAN, Sub-1GHz | Sub-1GHz |
| Web Servers Supported | Amazon AWS, IBM Watson | Amazon AWS, IBM Watson | Unknown | Unknown |
| Communications Range | long range | extremely long range | short range | long range |

LoRaWAN would be a nice addition, because it is less costly than SigFox (there is a small monthly fee associated with SigFox), but the range is significantly lower, power cost is higher, and setup cost is higher. As well, the most significant constraint for our project is the long-range and rate of transmission, in regard to which LoRaWAN would severely limit our project.

Of these chips, our best available choice is the Texas Instruments CC1352R. We have ordered and are currently developing for this chip. It was chosen for a multitude of reasons. The standby current is significantly lower than the other two chips, which will lower power required and overall maintenance costs in the long run. The range is reportedly as long as102 km, at 14 dBm, according to Texas Instruments. It supports many of the standards the we intend to use for the meshing and pushing protocols as well such as SigFox and Zigbee which requires Bluetooth. And it is capable of this feat because it can utilize the Sub-1GHz and 2.4 GHz bands simultaneously.

We will likely switch to the CC1352P which has a maximum range three-times the range of the regular CC1352R. As well, both chips come standard with a stepdown DC/DC converted (internal voltage regulator) for the MCU, which is programmable, exactly as we desired, so in testing we will decide whether or not we actually need a stepdown converted or voltage regulator still for further production. This will be done within the Implementation section.

Decibel-milliwatts is a measure used to indicate that a power ratio is expressed in decibels (dB) with reference to one milliwatt (mW), in other words dB * mW (dBm). It is used to express the power capacity of radio, microwave and fiber-optical communication networks and in our case, 50-Ohm impedance scale RF transceivers. Because the range of any RF device is most heavily dependent upon power output to the antenna, the dBm is the most important measure in determining range and is exponential as it increases. Another reason to switch to the CC1352P once available is that it outputs far more, using the same long-distance configuration as the CC1352R, and thus should more than double the effective communication range over the Texas Instrument CC1352 Sub-1GHz Transceiver.

### *GPS Chips*

Adding a GPS Chipset to our end-product will likely be difficult and expensive. But because of the necessity to Steven Eisele we are determined to find a cost-effective way to add active GPS-location from anywhere, anytime to our communications template end-product.

| **GPS RF Receiver** | **SE4150L** by Skyworks Solutions | **SE4110L** by Skyworks Solutions | **CSRG0530B01-ICKD-R** by Qualcomm | **STA8058-ND** by STMicroelectronics |
|---|---|---|---|---|
| Datasheet Available | Yes | Yes | No | No |
| Reference Designs Available | Yes | Yes | No | No |
| Availability | Available | Available | Available | Available |
| Minimum Order Quantity | 1 | 1 | 1 | 1000 |
| Price (USD) | $3.20 | $3.59 | $6.88 | $6.65 |
| Lead Time | Immediate | Immediate | 20 Weeks | 26 Weeks |
| Maximum Sensitivity (dBm) | Unknown | Unknown | Unknown | -159 |
| Current – Receiving (mA) | 15 | 10.5 | Unknown | Unknown |
| Voltage – Supply (V) | 2.7 – 3.6 | 2.7 – 3.6 | Unknown | 3 – 3.6 |
| Operating Temp. Range (Celsius) | -40 to 85 | -40 to 85 | Unknown | -40 to 85 |
| Data Interface | PCB, Surface-Mount | PCB, Surface-Mount | Unknown | PCB, Surface-Mount |
| Memory Size | none | none | Unknown | 256kB Flash NOR Mem IC, 64kB RAM |
| Package / Case | 24-VFQFN Exposed Pads | 24-VFQFN Exposed Pads | Unknown | 104-LFBGA |
| Device Packaging | 24-QFN (4x4) | 24-QFN (4x4) | Unknown | 104-LFBGA (11x7) |

With any GPS module we choose, within our price range, we will need to create a 15- to 25-mm size range patch antenna onboard PCB on the ground plane. We choose patch antennas because they provide better performance per size and lower cost and integration required compared to Linear GPS antennas (chip or dipole). As well, Linear GPS Antennas only receive signals from one axis resulting in less sensitivity and reduced coverage. We want greater coverage. *Patch antennas sold by Taoglas Limited are our best bet for tested GPS module antennas and allow a simple GPS interface.* More on this will be discussed in specific implementation details.

We have chosen to order both the SE4150L and SE4110L because they come with reference designs and ample information within the datasheets as to how to use these GPS receivers with other RF devices. This will be immeasurably helpful when integrating or interfacing the Texas Instruments CC1352R and CC1352P internal MCU with our custom GPS module. They do however consume a lot of current and will require their own power. As well, it is worth noting that we will have to add a lot of other parts to the PCB specifically for our custom GPS module featuring these receivers such as antenna, ASM sensors, and other filtering requirements for each input. This will add associated cost, as well as take up PCB space, so we have chosen the least expensive and smallest GPS receivers for that explicit purpose as well – the entire GPS module on our PCB will be expensive.

One possibility to decrease costs as well, is instead of using a baseband receiver IC to process the digital output of the GPS receiver, pushing all digital data from the GPS receiver immediately to the server. The digital data would then be processed using a software GPS baseband processor ("software GPS receiver") library for a programming language we are familiar with. One such library exists in the same spirit as Software-Defined Radio (SDR): GNNS Software-Defined Receiver.

In the meantime, we have also purchase the completed GPS module 474-DD-14239 Spark Fun GPS Receiver Module SMD-S1315F to be integrated with the communications template in the case that we cannot develop the GNNS Software-Defined Receiver in time.

### *Flash Memory Chips*

Because the memory on the Texas Instruments CC1352R and CC1352P that we are using is used for transmission purposes only we will need external Flash Memory ICs. We have two options here, NAND Flash and NOR Flash Memory ICs.

| Flash Mem. Type | NAND | NOR |
|---|---|---|
| Standby Power | High | Low |
| Cost-Per-Bit | Low | High |
| File Storage Use | Easy | Hard |
| Code Execution | Hard | Easy |
| Capacity | Hard | Easy |
| Write Speed | Fast | Slow |
| Read Speed | Slow | Fast |

| | | |
|---|---|---|
| Active Power * | Low | High |

*note that active power id dependent upon how the flash memory is used. NOR is typically slower in writes and consumes more power than NAND for this action. NOR is typically fast on reads, which consume less power.*

**NAND and NOR Flash Operating Specifications**

| | SLC NAND Flash (x8) | MLC NAND Flash (x8) | MLC NOR Flash (x16) |
|---|---|---|---|
| Density | 512 Mbits – 4 Gbits | 1 Gbit to 16 Gbits | 16 Mbit to 1 Gbit |
| Read Speed | 24 MB/s | 18.6 MB/s | 103 MB/s |
| Write Speed | 8.0 MB/s | 2.4 MB/s | 0.47 MB/s |
| Erase Time | 2.0 mSec | 2.0 mSec | 900 mSec |
| Interface | I/O – indirect access | I/O – indirect access | Random Access |
| Application | Program/Data mass storage | Program/Data mass storage | eXecuteInPlace applications and Data mass storage |

Both NAND and NOR flash memories have a place in embedded MCUs, however we will want to be using these MCUs for data storage, and not necessarily a lot of data so we do not necessarily care how much space we have. We will likely want to be using NAND in this case. The table below compares some options we have for NAND- and NOR-specific Flash memory for data mass storage and program storage.

| **Flash Memory IC** | **MX25R8035F M1L0** by Macronix | **S25FL116K0XMF I041** by Cypress Semiconductor | **SST25WF080B-40I/SN** by Microchip Technology |
|---|---|---|---|
| Memory Type | NOR Flash Mem. | NOR Flash Mem. | NOR Flash Mem. |
| Reference Designs Available | Yes | No | No |
| Cost | $0.77 | $0.59 | $0.94 |
| Available | Available | Available, but End-of-life (EoL) | Available |
| Key Features | Ultra-low power mode, high-performance mode, wide range VCC (1.65 – 3.6V) for RWP operations, unique ID and secure OTP | Variable read latency (number of dummy cycles) for faster initial access time or higher clock rate commands, industrial plus and | Ultra-low power mode, pin-count package which occupies less board space and lowers system costs, high performance fast CMOS SuperFlash |

| | | | |
|---|---|---|---|
| | support, multi I/O support (single, dual and quad), program interrupts | extended temperature range, volatile config option in addition to legacy non-volatile config. | technology, better long-term reliability and performance |
| Memory Size | 8Mb | 16Mb | 16Mb |
| Max CLK Freq. | 108MHz | 108MHz | 40MHz |
| Interface Type | SPI | SPI | SPI |
| Organization | 4K x 16 | 2M x 8 | 1M x 8 |
| Data Bus Width | 8 bit | 8 bit | 8 bit |
| Supply V. Min (V) | 1.65 | 2.7 | 1.65 V |
| Supply V. Max (V) | 3.6 | 3.6 | 1.95 V |
| Supply I. Max (mA) | 6 | 25 | 5 |
| Min Op. Temp. | -40 | -40 | -40 |
| Max Op. Temp. | 85 | 85 | 85 |
| Packaging | 8-SOIC | Tube | 8-SOIC |
| Pins | 8 | 8 | 8 |
| Connection Type | Surface Mount | Surface Mount | Surface Mount |

As it turns out, all of the NAND memory chips offered more memory, but were significantly more expensive and outside of our budget. So, we have only compared NOR Flash Memory ICs.

We have chosen the MX25R8035F M1L0 by Macronix because it has references designs already available for RF integration, and more specifically for the Texas Instruments CC1352R. It is also referenced specifically as the flash memory chosen by TI for the interface of the CC1352R, so it is the best possible choice in regard to this. Operating temperatures are within a suitable range, and the surface mount is ideal for soldering ourselves, as will be required of us. It is not the least expensive per memory, but it does have security and built-in features that will specifically aid our application, so while cost may remain in the middle-ground, it is well worth it to have the MX25R8035F as our NOR Flash Memory IC.

## Sensors

### *Temperature Sensors (Thermistors)*

The mount of this chip needs to be a surface mount, and the temperature sensor chip needs to be able to endure and sense temperatures from a minimum range of -40 ˚C to 85 ˚C. after taking all these specs into account, Plan Bee narrowed down possible chips. Some chips viewed include $I^2C$, but after reviewing multiple chips, a preferable output type not only includes $I^2C$ but SMBus as well.

The TMP112AIDRLT chip has one of the best accuracies of ±0.5˚C, but is also more expensive, costing $1.37 per 250 chips. This chip also has a higher resolution of 12b vs a resolution of 11b or 10b. The other two chips with 12b resolution are the TMP112NAIDRLT and the TMP112NAIDRLR, which are both the same TMP112 chips, but slightly different models. The difference between these three TMP112 chips is accuracy and price. The TMP112NAIDRLT has an accuracy of ±1˚C, and is also one of the more expensive chips, costing $1.22 per 250 chips. These previously specified chips have a lower range of operation temperature. None of these chips can be bought individually, so free samples would need to be requested. The MCP9808T-E/MC chip operates at a slightly higher voltage and has a lower resolution than the other chips, but does have a higher accuracy of ± 0.5˚C. The MCP9808T-E/MC does have a preferred packaging/casing of 8-TSSOP, 8-MSOP (0.118", 3.00mm Width), which is a variation to be seriously considered. These four sensors are showcased in the table below. Plan Bee ultimately decided to order the TMP112AIDRLT and the TMP112NAIDRLR because they are the most accurate and have the highest resolution. These two chips are also the same TMP112 sensor, but different models. Ordering both will be useful for comparisons later and will help Plan Bee decide which of the two sensors to use for the final prototype.

| Temperature Sensors | Manufacturer | Resolution | Accuracy | Temp. Operating Range | Price |
|---|---|---|---|---|---|
| TMP102AIDRLT | Texas Instruments | 11b | ± 2˚ C | -55˚C ~ +150˚C | $0.94/ 250 chips |
| TMP112AIDRLT | Texas Instruments | 12b | ± 0.5˚ C | -40˚C ~ +125˚C | $1.37/ 250 chips |
| TMP112NAIDRLT | Texas Instruments | 12b | ± 1˚ C | -40˚C ~ +125˚C | $1.22/ 250 chips |
| TMP112NAIDRLR | Texas Instruments | 12b | ± 0.5˚ C | -40˚C ~ +125˚C | $1.03/ 250 chips |
| MCP9808T-E/MS | Microchip Technology | 10b | ± 0.5˚ C | -40˚C ~ +125˚C | $.97/2 500 chips |

### *Internal Measurement Units (IMUs)*

We expect to implement an Internal Measurement Unit (IMU) chip. The MPU-9150 that was included on the test board is now outdated and no longer offered, so therefore cannot be considered in this comparison. The MPU-9250, however, is active and the newest version of this sensor is available from InvenSense. When looking at the specs for IMU's, the question arose of whether $I^2C$ was the only output type Plan Bee wanted to have on this chip. Plan Bee examined chips with only $I^2C$, as well as chips that offered a wider range of output types, such as SPI and UART. Some chips that only offered $I^2C$, such as the

BHI160, are just as expensive, if not more expensive, than chips with a variety of output types, such as the BNO080. Including more output types in this chip would hinder the budget of the project but it could be helpful to have varying output types. The MPU-9250 only offers $I^2C$ but is more advantageous in price. Next, Sensor type needed to be considered. All chips that contain $I^2C$, SPI, and UART have a wider range of sensor types than the chips with $I^2C$, which is another benefit of choosing one of the more flexible chips. Most chips with the ideal output type have sensor types of Accelerometer, Gyroscope, Magnetometer, and 9 Axis. The BNO080 and the BNO085 are both much cheaper if ordered in bulk (around $5), but that price rises to around $12 if bought individually. Free samples would preferably be requested. Both the BNO080 and the BNO085 chips are manufactured by Hillcrest Laboratories. The MPU-9250 was deemed to be the most useful due to the low cost. Low cost was ultimately deemed preferable to multiple output types.

| Internal Measurement Unit | Manufacturer | Output Type | Sensor Type | Temperature Operation Range | Price |
|---|---|---|---|---|---|
| **BNO080** | Hillcrest Laboratories, Inc. | $I^2C$, SPI, UART | Accelerometer, Gyroscope, Magnetometer, 9 Axis | -40°C ~ 85°C | $13.48/chip |
| **BNO085** | Hillcrest Laboratories, Inc. | $I^2C$, SPI, UART | Accelerometer, Gyroscope, Magnetometer, 9 Axis | -40°C ~ 85°C | $11.85/chip |
| **BHI160** | Hillcrest Laboratories, Inc. | $I^2C$ | Accelerometer, Gyroscope, 3 Axis | -40°C ~ 85°C | $12.40/chip |
| **MPU9250** | InvenSense | $I^2C$ | Accelerometer, Gyroscope, 3 Axis | -40°C ~ 85°C | $9.32/chip |

### *Pressure Sensors (Force Transducers)*

Pressure sensors will also be implemented in Plan Bee's design. The test board included the BMP-180 chip sensor, but this chip could not be compared because it is obsolete. A Surface Mount pressure sensor that operates under 4 Volts was prioritized due to the power source providing around 4V or less to the system. $I^2C$ is a needed output type, but if other output types are included with certain chips, those are preferable. It was discovered that most chips with only $I^2C$ did not include all the other specifications needed to progress in the selection process. Chips that fit the other ideal requirements seemed to have $I^2C$ as well as SPI included in their output types. After narrowing down output type, almost all remaining chips have the same output of 24b, except for the SSCMNN015PA5A3, which has an output type of 12b. Maximum pressure did not need to be extremely high, so the 290.08 PSI is acceptable for most of the sensors. The SSCMNNN015PA5A3 has a maximum pressure of 30 PSI (206.84 kPa). Although a high maximum pressure is not needed, the highest degree of accuracy is crucial for Plan Bee's project; ±.015 PSI is as minimum of an accuracy range as possible that all chips compared need to have. The SSCMNN015PA5A3 does not meet this accuracy requirement and is also twice as expensive as all other chips compared.

The chip selected also needs to have a minimum temperature operation range of -40°C to 85°C. After narrowing chips down using these requirements, the remaining chips all have a few differences, which include operating pressure range, packaging/casing, the supplier device package, and price. These differences are previewed in the table below. Most chips below are produced by STMicroelectronics. Plan Bee decided to go with the most inexpensive chip, the LPS22HBTR.

| Pressure Sensor | Manufacturer | Operating Pressure | Packaging/ Casing | Supplier Device Package | Price |
|---|---|---|---|---|---|
| LPS22HBTR | STMicroelectronics | 3.77 PSI ~18.27 PSI (26 kPa ~ 126 kPa) | 10-WFLGA Exposed Pad | 10-HLGA (2.0x2.0) | $3.28/chip |
| LPS22HDTR | STMicroelectronics | _ | 10-VFLGA | 10-HLGA (2.0x2.0) | $3.96/chip |
| LPS33HWTR | STMicroelectronics | 3.77 PSI ~18.27 PSI (26 kPa ~ 126 kPa) | LGA | 10-CCLGA (3.3x3.3) | $8.83/chip |
| SSCMNNN015PA5A3 | Honeywell Sensing and Productivity Solutions | 15 PSI (103.42 kPa) | 8-SMD, J-Lead | 8-SMT | $23.13/250 chips |

### *Light Sensors (Photodetectors)*

Plan Bee also expects to add a light sensor to the prototype board. For this project, the light sensor needs to be an ambient light sensor operating with an output type of $I^2C$ (a variety of types are not available with this chip). The sensor chosen also needs to operate on less than 4 Volts and must be a surface mount type chip as well. Plan Bee has previously decided that the minimum temperature should never be above -40 ˚C, nor should the maximum temperature ever drop lower than 85 ˚C. Only specific sensors that have these minimum requirements are included in comparison. Intersil manufacturing produces many similar chips with these specs. The 5 Intersil chips are all extremely similar, mainly varying in price. The APDS-9250 sensor, produced by Broadcom Limited, would be cheapest if a free sample could be obtained. The OPT3001DNPR is also cheaper when bought in bulk but may not be available for Plan Bee. Both bulk order sensors have similar specs to the other chips, as compared in the table below. If free samples cannot be obtained, the cheapest chip left will be what Plan Bee decides to use, which is the ISL29023IROZ-T7. If free samples can be obtained, The OPT3001DNPR would be chosen due to the more ideal voltage supply range.

| Light Sensors | Manufacturer | Voltage Supply Range | Temperature Operation Range | Price |
|---|---|---|---|---|
| ISL29023IROZ-T7 | Intersil | 2.25 V ~ 3.63 V | -40˚C ~ +85˚C | $3.43/chip |
| ISL29020IROZ-T7 | Intersil | 2.25 V ~ 3.63 V | -40˚C ~ +85˚C | $4.26/chip |
| ISL29033IROZ-T7 | Intersil | 2.25 V ~ 3.63 V | -40˚C ~ +85˚C | $4.08/chip |
| ISL76683AROZ-T7 | Intersil | 2.5 V ~ 3.3 V | -40˚C ~ +105˚C | $4.23/chip |
| ISL76683AROZ-T7A | Intersil | 2.5 V ~ 3.3 V | -40˚C ~ +105˚C | $4.64/chip |
| APDS-9250 | Broadcom Limited | 1.7 V ~ 3.6 V | -40°C ~ 85°C | $.91/2500 chips |
| OPT3001DNPR | Texas Instruments | 1.6 V ~ 3.6 V | -40°C ~ 85°C | $1.27/3000 chips |

### *Humidity and Moisture Sensors*

Humidity and Moisture sensors are applicable for Plan Bee's Design as well. For this sensor to be useful for this project, it needs to be a surface mount, relatively accurate, support an output type of $I^2C$, have a full humidity range of 0% to 100%, and operate on under 4 Volts. After considering the specs above, there are no chips that Plan Bee could find that fit the requirements while also including ￼ and SPI, so ￼ alone was chosen. Looking at response time, a fast as possible response time is preferred. Some chips have lower response times, such as 18s and 10s, far slower than the 8s and 5s of many other chips. Some of these types of sensors are also unavailable for immediate delivery; Plan Bee would like the chips delivered as quickly as possible. Because of response time disparities as well as delivery time, only 4 chips are compatible with Plan Bee's project.

| Humidity and Moisture Sensors | Manufacturer | Voltage Supply Range | Response Time | Output | Price |
|---|---|---|---|---|---|
| HPP845E031R4 | TE Connectivity Measurement Specialties | 1.5 V ~ 3.6 V | 5s | 12b | $2.88/400 chips |
| SHT21 | Sensirion AG | 2.1 V ~ 3.6 V | 8s | 12b | $4.21/400 chips |

| | | | | | |
|---|---|---|---|---|---|
| SHT25 | Sensirion AG | 2.1 V ~ 3.6 V | 8s | 12b | $6.97/400 chips |
| HDC2010YPAT | Texas Instruments | 1.62 V ~ 3.6 V | 8s | 11b | $1.71/250 chips |

The HPP845E031R4 has the fastest response time out of the four chips, as well as one of the cheapest prices. The HDC2010YPAT is also cheaper especially because less parts are required per order; however, this chip has a slower response time. The output of the HDC2010YPAT is 11b whereas all 3 others have an output of 12b. The different packaging/casing is preferred to be a 6-TDFN Exposed Pad, which is what the first three sensors come in. The HDC2010YPAT was ultimately chosen for this project because of the wider voltage supply range and lowest available.

## Constraints

Initial research into project constraints that will limit our end-product, such as interviews with the sponsor, Steven Eisele, in the Project Description section is expanded upon within this section. Design constraints follow the IEEE standards, going over Economic, Temporal, Environmental, Ethical, Health & Safety, Production, Sustainability, and Security constraints. Within the Standards subsection we discuss necessary standards and tutorials on how these standards will be applied to our project, and how each standard is grouped and related. Barriers to Market entry are also included here, because we may be marketing this device toward other beekeepers, and the device will need to be mass produced regardless. This means that the FCC, and other governing boards, as well as other companies, may impede us in realization of our end-product.

### Design Constraints

#### Economic

The end-product will need to be economical enough to put on every hive within Pollination USA's apiaries. Because of this, it should not exceed more than about one-third of the fixed cost of setup of a new commercial beehive, according to Steven Eisele.

**Table 1:** Typical Expenses for Setup and Upkeep of an Individual, Small Commercial Beehive

| Type | Purpose | Expense |
|---|---|---|
| **fixed one-time costs** | small commercial hive | $200.00 |
| **fixed recurring costs (monthly)** | food | $20.00 |
| | medication | $30.00 |
| | insurance including drought and commercial beehive | $1.20 |
| **variable recurring costs (monthly)** | labor | $12.40 |
| | transportation | (X) |
| | hive loss | (X) |

* The (X) indicates that the expense is dependent upon contracts and other factors that cannot be linearly estimated on a monthly basis.

With the given constraint, $70 implementation cost per device, at 5,000 units – on the conservative end of the number of individual beehives owned by Pollination USA – gives us some leeway in design. Our most expensive individual components given our financial projections will be individual load cells and solar cells. We may still be able to reduce these costs further.

The cost of server maintenance or usage should also not exceed one-third of the monthly cost of labor and insurance combined. With this constraint we have a limitation of $4.54 per hive per month on cost of data analysis and storage. This is above the expected costs for using the available IBM Watson and Amazon AWS cloud services. So, these cloud services are still within our economic constraints. This is discussed further in Implementation.

### Temporal

Our project needs to be completed a month before the end of Senior Design II to meet the requirements of our degree path. All design and development processes will be constrained by the five-month period, at the end of which our end-product must be functional and not just a prototype. We discuss this in more detail within the Milestones section below.

Steven Eisele will be in the Pacific Northeast fulfilling a contract until the end of Summer, as well. Although many beehives will remain in the Everglades during Summer, we will not be able to test our product with his oversight until – at the earliest – early September.

### Environmental, Communications & Power

Our end-product will be attached directly to the side of a commercial-style beehive; the appearance of this is much like a dresser with drawers, which function as partitions of the beehive. These hives are commonly left in remote locations, more than twenty-five miles away from urban environments. Pollination USA's main yard is about one-hundred miles South-East of Fort Myers, within the Everglades. The tropical-swamp environment of the Everglades provides unique design problems for our sensitive electronics:

- high humidity and daily precipitation,
- salinity of near-ocean air,
- high pressure storm systems moving through South Florida,
- extreme heat (120 F)

As well, Mr. Eisele has noted that he has regular contracts with remote farms in California and in the Pacific-North-West, and the beehives he manages are transported there. Because of this, he would also like the same end-product to work in dry, desert environments and extreme-cold environments (down to 0 F) with snow.

Because of the remote location of the hives, cellular communications channels will not be available. We are thusly constrained to options including satellite communications, building our own cellular base station, or long-range radio-frequency (RF) communications. Satellite communication systems and cellular base stations are prohibitively expensive, so we are left to RF. The remote location will also present issue with powering the device. The best option for us is then to use solar technology in unison with an ultra-low power communications device.

### Ethical, Health & Safety

Our end-product will increase the efficiency of work completed, thereby reducing the number of man-hours required upon each beekeeper working for Pollination USA. This may displace jobs. Insurance cost per beehive may also decrease. And if we manage to create the functionality required for the feeding and medication control system that automates non-health maintenance of the individual beehives, then the number of jobs displaced will increase significantly. This is then entire intent of the system though, to save Pollination USA expense. This is not to say that there will not still be beekeepers – there will – just that these beekeepers may not be doing as much "beekeeping" as they would maintenance. In order to assist in the maintenance of our end-product, we should create a user-manual following this document, requiring minimal IT-experience so as not to require them to be completely retrained. We may, as well, be required to train them on the use and maintenance of our end-product.

On the issue of bystander health, it is possible that the radiofrequency (RF) signal energy could be potentially hazardous to those nearest to these signals, and thereby nearest to our devices, the beekeepers. The FCC has maintained wireless communications standards since 1996 on the issue of RF signal energy exposure limitations for human safety, for all communications devices produced and sold in the United States. [14] The FCC firmly limits exposure to RF energy from wireless communications devices to 1.6 watts per kilogram (W/kg) as averaged over one gram of tissue.

It is possible that a non-beekeeper passerby could be stung by Pollination USA's bees; it is also possible that they could have an allergy toward bee sting venom. Honeybees, the majority of the bees kept by Pollination USA, are typically docile until an – as determined by the bees – aggressive intruder approaches within ten feet from the hive. [15] It might be possible to somewhat prevent a non-beekeeping passerby from being stung by incorporating a warning that would somehow alert to the presence of bees, while simultaneously not disturbing the bees. This can be an additional feature of our system.

## Production & Sustainability

Researchers have proven that honeybees' behavior can be disturbed radiofrequency-spectrum electromagnetic fields (RF-EMF). [16] With emitted RF-EMF band above 1 μW/m2 at honeybee-significant frequencies of between 110 Hz and 405 Hz – applied for longer than 45 minutes – is proven to intensify the amplitude and frequency of vibration of the honeybees and aggravate them into an "attacking" state beyond the ordinary limits of the hive, and out of the desirable production and brooding states. This research places a lower-limit constraint on the frequencies of communications we can use for long-distance communications.

The biggest environmental sustainability factor for our end-product is electronic waste and re-usability of the frame-worked device. Our biggest concerns are with the powering of the device – the solar-cell battery (of type Nickel-Cadmium, or NiCad) and the solar cell themselves. We are not as concerned with the durability of replaceable and recyclable sensors and chip electronics. NiCad batteries are the only type that can be used within our extreme temperature constraints, but they have hazardous downsides and typical durability is between seven to ten years. [17] They will however be easily replaceable within our system for the purpose of sustainability and lowering replacement (of whole electronics) cost, so when they are prime for replacement, we need to have an environmental-safety disposal plan ready. This will be an amended section to the user-manual.

## Security

The benefits to Pollination USA in our internet-of-things (IoT) sub-1GHz communication template implementation can instead become a huge liability of privacy and businessautonomy loss without proper security protocols in place. [18] As such, the data that is being sent should be secured and encrypted. Further security and encryption constraints domestically are discussed in the software standards section.

As discussed previously, beehive-theft is a somewhat-significant cause of loss to domestic commercial apiaries, like Pollination USA. [19] We have discussed the addition to our end-product whereby every IoT template is to include an embedded GPS locator module, in addition to its 10-mile sub-1GHz range. And an immediate alert whenever the hive is moved, using accelerometers as motion sensors. These must be non-detachable integrated parts within the beehive. With this added constraint, immediate feedback gives rise to immediate measures that can be taken to prevent beehive-theft losses.

Another concern that Steven Eisele had was natural security breaches, of the weather-related and animal-related types. He added that some apiaries, such as his own, already have electric fences installed around each yard to deter wildlife, and he would like a control system to see when the electric fence is tripped – perhaps by a bear – and when this occurs he would like to see images to ensure that the hives are generally unharmed for a period of time after. It would be generally useful to him to receive periodic image updates of each yard, every three-to-four hours, always. In addition to these periodic updates, whenever the motion sensors or weather sensors – perhaps by adding rainfall sensors – attached to the hives are tripped, image updates and alerts are sent in a "burst" over a brief period of time following the event. These added constraints give the apiarist peace-of-mind to know what security threats their honeybees are facing in any yard at any given time.

## Standards

### Hardware

For this section we sought to contrast the available standards and illustrate the reason behind our decisions to adopt the specified features.

#### *Weather-Resistant Enclosures*

#### IPMS – International Protection Marking Standards

As presented in the engineering and marketing specifications, a weather resistant enclosure will be a critical component to the overall device operability. As such, we have researched possible methods of weather proofing the data-collecting device. Enclosures are the most fundamental forms of protecting electronics from the weather. There are currently 2 standards available in United States, for protection; International Protection Marking Standard (IP), and NEMA weather resistance. The figure below shows the IPxx marking system determinations. (Ingress Protection Ratings Explained, n.d.)

| Solids | | Water | |
|---|---|---|---|
| 1 | Protected against a solid object greater than 50 mm, such as a hand. | 1 | Protected against vertically falling drops of water with limited ingress permitted. |

| | | | |
|---|---|---|---|
| 2 | Protected against solid objects greater than 12.5 mm, such as a finger. | 2 | Protected against vertically dropping with enclosures tilted up to 15 degrees from the vertical axis. Limited ingress permitted. |
| 3 | Protected against a solid object greater than 2.5 mm, such as a screwdriver. | 3 | Protected against vertically sprays of water up to 60 degrees from the vertical axis. Limited ingress protection for three minutes. |
| 4 | Protected against a solid object greater than 1 mm, such as a wire. | 4 | Protected against water splashed from all directions. Limited ingress permitted. |
| 5 | Dust Protected. Limited ingress of dust permitted. Will not interfere with the operation of the equipment. Two to eight hours. | 5 | Protected against jets of water. Limited ingress protection. |
| 6 | Dust Tight. No ingress of dust permitted. Two to eight hours. | 6 | Water from heavy seas or water projected in powerful jets shall not enter the enclosure in harmful quantities. |
| | | 7 | Protected against the effects of immersion in water between 15 centimeters and 1 meter for 30 minutes. |
| | | 8 | Protected against the effects of immersion in water under pressure for long periods of time. |

*IPxx – Ingress Protection xx:*
*the first x is the numerical standard abided by for Solids;*
*the next x is the numerical standard abided by for Water.*

The bare minimum of protection we need is IP63, to protect fully against heavy rain and dust. However, IP66 is the most common weather-resistant enclosure standard abided and is more thusly more readily available and less expensive for our product dimensions. IP66 offers further protection against total dust ingress, total immersion protection between 15 cm and 1 meter below water but offers limited water ingress protection beyond this depth. (NEMA Enclosure Standards, n.d.)

The international protection marking standards classify and rate the degree of protection provided by an enclosure against external elements such as dust, rain, and physical force. To meet the weather resistant and dimensions listed in the requirement specification, we've opted for a Sonoff IP66 rated waterproof enclosure, as shown below. [CITE]

*Figure 0-1: Sonoff IP66 Waterproof Case*

The enclosure will be large enough to meet our needs while providing two additional outputs for attaching external sensors and an additional output for the Sub-1 Ghz and Bluetooth antenna.

### NEMA – North American Enclosure Types

NEMA outlines North American Standards for different indoor and outdoor enclosure types; each type of enclosure contains different standards. Because Plan Bee's enclosure will be outdoors, deciding which enclosure to use can be done by observing each type of outdoor enclosure's standards. NEMA has several different enclosure types. Plan Bee is focused on having a waterproof enclosure that is resistant to minerals as well. The table below illustrates the degree of protection several types of NEMA enclosures offer. (NEMA Enclosure Types, n.d.)

| **Offers A Degree of Protection Against the Following Conditions** | **Type of Enclosure** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **1 *** | **2 *** | **4** | **4X** | **5** | **6** | **6P** | **12** | **12K** | **13** |
| Access to Hazardous Parts | X | X | X | X | X | X | X | X | X | X |
| Ingress of Solid Foreign Objects (falling dirt) | X | X | X | X | X | X | X | X | X | X |
| Ingress of Water (such as dripping or light splashing) | … | X | X | X | X | X | X | X | X | X |
| Ingress of Solid Foreign Objects (circulating dust, lint, fibers, etc.) ** | … | … | X | X | … | X | X | X | X | X |
| Ingress of Solid Foreign Objects (falling dust, lint, fibers, etc.) ** | … | … | X | X | X | X | X | X | X | X |
| Ingress of Water (Hose-down and splashing water) | … | … | X | X | … | X | X | … | … | … |
| Oil and Coolant Seepage | … | … | … | … | … | … | … | X | X | X |
| Oil or Coolant Spraying and Splashing | … | … | … | … | … | … | … | … | … | X |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Corrosive Agents | … | … | … | | … | … | X | … | … | … |
| Ingress of Water (Occasional Temporary Submersion) | … | … | … | … | … | X | X | … | … | … |
| Ingress of Water (Occasional Prolonged Submersion) | … | … | … | … | … | … | X | … | … | … |

**These enclosures may be ventilated.*
***These fibers and flyings are nonhazardous materials and are not considered Class III type ignitable fibers or combustible flyings. For Class III type ignitable fibers or combustible flyings see the National Electrical Code, Article 500.*

Given the information presented in the table above, a set of enclosure type classifications were narrowed down into four distinct categories that we could utilize for our end-product:

1. Type 4 Enclosure indicates protection against falling dirt, light splashing, circulating dust/fibers, and settling dust/fibers.
2. Type 4X Enclosure indicates protection against all hazards that type 4 includes, as well as protection against corrosive elements.
3. Type 6 Enclosure indicates protection against all type 4 prevented hazards as well as Occasional temporary submersion.
4. Type 6P Enclosure indicates protection against all hazards protected under type 4X, as well as occasional temporary submersion and occasional prolonged submersion.

### *Hazardous Substances & Safety*

### ROHS – Restrictions of Hazardous Substances Directive

Restrictions of Hazardous Substances Directive is a standard developed and enforced by the European Union. This standard has been in effect since 2003. This standard promotes recycling of products in a cheaper way for consumers. Because the materials need to be recyclable, certain recourses must be barred from usage in the products under this standard. Such materials include lead, mercury, and certain harmful flame retardants.

### PCB FR-4 – Flame Retardant

A NEMA designation for Flame Retardant Printed Circuit Boards. Made with Fiberglass-reinforced epoxy-laminated sheets; such boards are commonly used as the fundamental elements in circuit boards because of how versatile they are. They can withstand high temperatures, are low cost, and work well as an electric insulator. These boards work well in a variety of weather conditions. These boards work well with RF because of the dielectric capabilities and temperature variability. Moisture can also be an issue with RF, which is another reason why this board, with the ability to be highly weather resistant, is a capable choice. (FR4 Guide, n.d.)

### *Interconnect Communications*

#### UART – Universal Asynchronous Receiver-Transmitter

This is a configurable, hardware-driven, serial communication device. It is usually connected to an external driver circuit to meet the electric signaling levels required by the RS232 communication protocol. Numerous UART devices are commonly integrated into integrated circuits and are commonly used for serial communication. The CC1352R relies on UART to communicate between its microcontroller and wireless transceiver. There are also 2 additional UART devices: one of which will be used for debugging and testing.

#### SSI – Synchronous Serial Interface

This communication protocol utilizes synchronous data transmission to transmit information without the need of an external clocking signal. Synchronous data transmission relies on the synchronization of an internal clock which dictates elapse time for incoming data. This maximizes bandwidth while reducing the amount of signals needed for serial communication. It is used extensively for RS-422 and RS-485 communication. Because of its benefits, it is routinely used for simplex communication which makes it well suited for sensor communication; it has become the de-facto standard among sensor manufacturer's. For this project synchronous serial interface will be used to log sensors data from externally connected devices; an RS485 driver has been proposed to be used to driver the necessary circuitry.

#### SPI – Serial Peripheral Interface Bus

Like SSI, SPI is a synchronous serial interface, commonly used for communication between onboard interconnects. SPI electric signaling relies on single-ended signaling instead of differential signaling. As a result, SPI communication is limited in range and will not be used for external device communication in this project. The CC1352R supports both SPI master and slave at a bus clock of up to 4 MHz.

#### JTAG – Joint Test Action Group

The standard used to verify and test printed circuit board designs after manufacture. To complement digital simulations, JTAG allows an engineer to perform on-chip instrumentation and electronic design automation (EDA). It defines a communication protocol and interface for accessing device level sub-blocks and provide device debugging, instruction tracing, and data tracing infrastructures. While JTAG define a broad set of protocols, many manufacturers routinely implement only a subset define implementation details. As such, it is important to refer to manufacturer specification for further insight.

### *Encoding & Modulation Communications*

Encoding is the first step in transmission of a data across a communications channel. Modulation follows this, before the transmitter-antenna transmits this digital data.

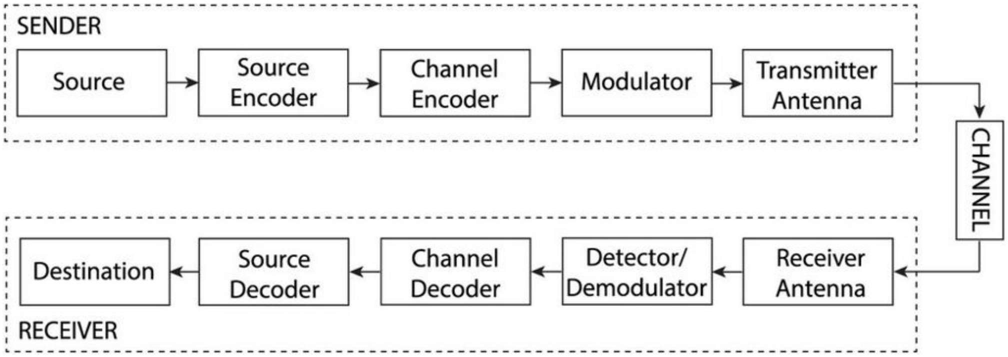


*Figure 0-2: Digital Communication Systems Block Diagram*

The following standards cover different methods of encoding and modulation that we are going to employ for our communications template end-product. (Modern Digital Analog Communications, n.d.)

### GFSK – Gaussian Frequency-Shift Keying

There are two main methods whereby this is accomplished. The first, GFSK is a communications standard for utilizing frequency-shift-keying (FSK). FSK is a modulation technique, whereby the frequency of a carrier signal, used to transmit digital information, is altered to symbolize binary information. Gaussian frequency-shift keying applies a Gaussian filter to the data signal. This reduces sideband power and channel interference. This technique is employed by LPWAN manufacturers, including Texas Instruments, and Sigfox. Low powered Bluetooth 5 also relies on this GSK modulation to limit out-of-band interference.

### GMSK – Gaussian Minimum-Shift Keying

Similar to GFSK, GMSK is a standard for minimum-shift keying (MSK) encoding of data. MSK is a type of FSK that encodes bits alternating between the quadrature components with the Q-component delayed by half of the symbol period. Dissimilar to FSK, the bits are encoded as half-sinusoids so that the resultant transmitted signal is constant-modulated (constant envelope) allowing for continuous-phase FSK scheme. In GMSK however, the digital data stream is first shaped by a Gaussian filter before being applied to a frequency modulator (encoder) and typically has a much narrower phase shift and transmission band; the benefit of this scheme is reduced sideband power, which in turn reduces out-of-band interference between the signal carriers and adjacent frequency channels. GMSK is used in GSM, for the purpose of cellular communications, and by GPS-AIS for maritime navigation (under GPS-WAAS). (Electromagnetic Devices, n.d.)

### CSS – Chirp Spread Spectrum Modulation

CSS, which we are going to called Chirp, is a spread spectrum technique that uses wideband linear frequency modulation chirp pulses to encode information. A chirp is a sinusoidal signal of frequency increase or decrease of time, often with a polynomial expression for the relationship between time and frequency. Below is a graph of a modulated upchirp; the vertical axis is amplitude and the horizontal axis is time, although values do not matter at this point. (IEE Explore, n.d.)

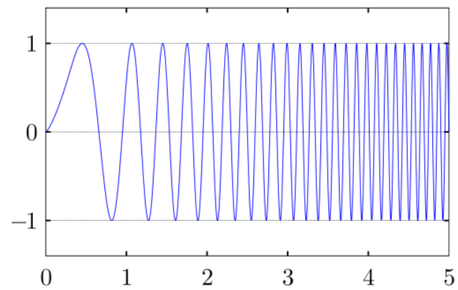



*Figure 0-3: Linear Frequency Modulated UpChirp in the Time Domain*

Chirp is a technique used to form the physical layer of LoRaWAN. Because LoRaWAN uses chirp to transmit over large distances in the sub-1GHz band range – specifically the 868MHz band – we will be using Chirp for transmitter-receiver modulation and demodulation. (IEE Explore, n.d.)

## GPS – Global Positioning System

The GPS is a US government owned utility that provides user with real-time positioning, navigation and timing data. It consists of the space segment which includes operating satellites, the controls segment which monitors the satellite, and the user segment which will include our application. (GPS systems, n.d.) There are four GPS sub-standards:

1. GPS-SSP – Standard Positioning Service Performance is used by the general public "user" applications of GPS, such as cellular phones, vehicular navigation systems, and others similar. This is the GPS standard we will be utilizing for our project.
2. GPS-WAAS – Wide-Area Augmentation Service Performance is used for aviation and marine applications, which translates to usage in airplanes and boats for navigation in unique spatial settings.
3. GPS-PPS – Precision Position Service Performance is used for military applications and is only available to the US military and NATO allies.
4. GPS-CM – Civil Monitoring Performance Specification is a compilation of requirements specifications and standards required to monitor the GPS civil service and signals based on top-level requirements to monitor all signals at all times and is used by the Department of Transportation for tracking of navigation-enabled motor vehicles. This includes services utilizing Navstar. (SPS performance, n.d.)

## GSM – Global System for Mobile Communications

Published and updated by ETSI (European Telecommunications Standards Institute), GSM specifies the use of Gaussian Minimum Shift Keying (GMSK) modulation standards explained prior, with Time Division Multiple Access (TDMA) for the use of data transmission in the 900 and 1800 MHz bands in Europe, and the 800 and 1900 MHz bands in North America. As the name lends itself to be interpreted, GSM sets the global standard for cellular communications networks used by mobile devices, including cellular phones, tablets, and other fringe Internet-of-Things devices. This standard is up-to-date from 1G to 4G communications protocols.

### 4G-LTE – 4-GSM Long-Term Evolution

This is a high-speed wireless communication standard for phones and always connected devices. It is developed and managed by the 3rd Generation Partnership Project (3GPP) (LTE (Telecommunication), n.d.). The specification defined a downlink rate of 300 Mbit/s and uplink of 75 Mbit/s, and a transmission latency of less than 5 milliseconds in the radio access network. LTE relies on frequency division duplexing (FDD) or time division duplexing (TDD) to manage data transmission and reception.

### GPRS – General Packet Radio Service

GPRS, established by ETSI, is a packet-oriented mobile data standard within GSM limiting packet size, formatting, and data speeds for guaranteed Quality-of-Service in 2G, 3G and 4G (LTE) networks. It will likely amend its standards for 5G networks which are being researched currently, continuing in relevance long into the future. The GPRS Core Network is the primary function of GPRS which allows 2G, 3G and WCDMA mobile networks to transmit IP packets to external networks through the Internet. Because we will be making use of the 3G and 4G technologies with TI CC1352R, and 1352P eventually, we will be utilizing this standard. The table below displays the coding schemes and associated speeds for the GPRS subset of standards:

| GPRS Coding Scheme | Bitrate incl. RLC/MAC * (kbits/s/channel) | Bitrate excl. RLC/MAC (kbits/s/channel) | Modulation Type | Code Rate |
|---|---|---|---|---|
| CS-1 | 9.20 | 8.00 | GMSK | 1/2 |
| CS-2 | 13.55 | 12.00 | GMSK | 2/3 |
| CS-3 | 15.75 | 14.40 | GMSK | 3/4 |
| CS-4 | 21.55 | 20.00 | GMSK | 1 |

** Cited in several sources (TS 45.01 Table 1), is the determined bitrate including RLC/MAC headers but excluding the uplink flag (USF) which is part of the MAC header, yielding a bitrate 0.15 kbits/s/channel lower.*

The Bitrate including RLC/MAC overhead is the rate at which the RLC/MAC layer protocol data unit (PDU) is transmitted; this consists of the MAC header, RLC header, RLC data unit and spare bits. The RLC data unit represents the payload, the rest of "overhead". The PDU is encoded by the convolution code specified for a particular GPRS coding scheme, which yields the same PHY layer data rate for all coding schemes. We will not be able to utilize this full data rate. (Electronics Notes, n.d.) (GPP, n.d.)

The next bitrate here is the rate at which the RLC/MAC layer payload (the RLC data unit) is being transmitted. As such, this bitrate excludes header overhead from the RLC/MAC layers. It is the amount of data we can actually use to transmit in kbits/s/channel.

### UMTS – Universal Mobile Telecommunications System

UMTS is a subset of standards of the International Telecommunications Union IMT-2000 standards and sets telecommunications standards for cellular devices using third-generation GSM standards, 3GPP (3rd Generation Partnership Project). In other words, the use of UMTS will enable us to use the Basic 3G cellular network, allowing a maximum data transmission rate of 300 Kilobits per second within the Sub-1GHz communications band.

### *Encryption Communications*

### AES – Advance Encryption Standard

This is an encryption standard used to secure data for remote transmission. The algorithm used to define the encryption is symmetric, meaning a single key will be able to encrypt and decrypt data files. AES has been adopted by the federal government and is the only key cipher approved by the NSA.

### SHA2 – Secure Hash Algorithm

Algorithms that secure data by sending it through bit strings of a fixed size in only a single, non- invertible direction in order for it not to be intercepted. This is encrypted and analyzed on the receiving end and compared to a specific bit value, making it the only way to obtain the information.

### ECC – Elliptic Curve Cryptography

Ecliptic Curve Cryptography is a replacement cryptography for Public Key Cryptography. As the NSA web archives state, "While at current security levels elliptic curves do not offer significant benefits over existing public key algorithms, as one scales security upwards over time to meet the evolving threat posed by eavesdroppers and hackers with access to greater computing resources, elliptic curves begin to offer dramatic savings over the old, first generation techniques." (Elliptic Curve, n.d.) ECC is a cost-efficient technology when compared to past technologies, especially over time. Past systems that applied public key were recommended for upgrade by NIST, and ECC was a viable successor.

### RSA – Rivest-Shamir-Adleman Encryption

Rivest-Shamir-Adleman Encryption can also be called Public Key Cryptography. RSA bit-keys are considerable longer than the keys used today, such as ECC. RSA is a system utilizing public key; this system is more outdated than ecliptic key. The table below illustrates the NIST recommended key sizes, comparing Symmetric Encryption, RSA and Diffie-Hellman Encryption, and Elliptic Curve Encryption.

| Symmetric Key Size (bits) | RSA and Diffie-Hellman Key Size (bits) | Elliptic Curve Key Size (bits) |
|---|---|---|
| 80 | 1024 | 160 |
| 112 | 2048 | 224 |
| 128 | 3072 | 256 |
| 192 | 7680 | 384 |
| 256 | 15360 | 521 |

The greater the key size in bits, the more encryption and safer the data being transferred through a wireless channel. We will be using RSA standards with Diffie-Hellman Key Agreement, explained below, as they are proven industry standard encryption methods wireless communications. (Elliptic Curve Cryptography, n.d.)

### Diffie-Hellman Key Agreement

Diffie-Hellman Key Agreement uses the public key system and private key system like the RSA does. When combining the use of a public key from one user with a private key from another, a secret encryption key may be shared between the two parties. This key can be used to encrypt data. (IETF, n.d.)

### DSA – Digital Signature Algorithm Encryption

The Digital Signal Algorithm is a Federal Processing Standard. A DSA falls under the Digital Signal Standard. The DSA is a standard used in the DSS. The DSS implements digital signature in leu of written signature. There are two components of the DSS, which are the creation of the digital signature itself, as well as the verification of that signature. Different keys are used for these two key components. Signature design itself uses a private key, whereas signature verification uses a public key. Public keys are used in many variations of systems, including RSA. (NIST, n.d.)

## Software

Software Communications

### TCP – Transmission Control Protocol

TCP is the main protocol in the Internet Protocol (IP) Suite, at the "Transport Layer". It provides reliable, ordered and error-checked delivery of a stream of bytes between applications running on a hosted web server communicating via an IP network (usually masked for encryption). All web-based applications such as the World-Wide-Web, email, remote administration and FTP (File-Transfer-Protocol) rely on TCP. Because our application will be hosted on a web server, and require encrypted communication via an IP network, this standard is integral for server-side development. (Principle of Network Design, n.d.) (TCP Parameters, n.d.)

### IPvx – Internet Protocol Version X

IP, meaning Internet Protocol, is the principal communications standard for the Internet Protocol Suite, and sits at the "Internet Layer". It provides relaying of datagrams across network boundaries, and its routing function enables internetworking, i.e. the "Internet". IP specifies how data is divided into packets from the source host to the destination host based upon the IP addresses in the packet headers and encapsulates this data to be delivered. (Technet, n.d.)

IPv4 is the predecessor of IPv6; the most prominent difference from version 4 is the size of the addresses, from 32-bits for addressing in IPv4 to 128-bit addressing in IPv6, allowing the number of internet addresses to expand by almost 29 orders of magnitude (x 1029). IPv4 is still the dominant IP standard, although IPv6 is growing quickly. The IP version we use will depend upon the web-server host that assigns our address. Because we will be establishing our server-side a new, we prefer to be using the newest standard under adoption, IPv6. (IP Network, n.d.) (MBS Standards, n.d.)

### UDP – User Diagram Protocol

UDP mostly aids as an interface between high layer networking processes and the internetworking of IP. UDP is the successor to Transmission Control Protocol. It is less complex; UDP does not have some of the unnecessary qualities that TCP contained. This decrease in complexity also increased performance of UDP. Because of this lack in complexity, UDP cannot be used in as many applications as TCP. (UDP Overview, n.d.)

### NanoIP – Nano Internet Protocol

NanoIP is a networking protocol; it works well with connectivity to devices, even when first connecting through a gateway. This technology is designed to bring networking to devices, but without the complexity of TCP. This standard contains nanoUDP and nanoTCP. NanoIP does not actually use IP addresses, but rather MAC addresses. NanoIP is faster and more simple than alternative protocol that uses IP. (IEE Explore, n.d.) (NanoIP, n.d.)

### CoAP – Constrained Application Protocol

CoAP is useful because it is designed to still be useful when more advanced technology comes about. It has also been designed to work on inexpensive technology, making it cost effective. With CoAP, resources can be easily accessed under a URL. This technology is efficient and has a similar style as a few other protocol, such as HTTP, making it user friendly. CoAP uses UDP as well as IP to operate with simplicity. (CoAP, n.d.)

### DDS – Data-Distributed Service for Real-Time Systems

DDS is and API standard from OMG (Object Management Group). DDS assimilates components of a system together with low-latency and dependability. Using this protocol simplifies the process of passing data so that consumers can focus on creating their specific product. This standard has a high-performance rating when compared to similar technologies and condenses the amount of time and work that needs to be put into developing a product. (Portals, n.d.)

### SOAP – Simple Object Access Protocol v1.2 (latest version)

SOAP is known for its simplicity and flexibility. SOAP attains these features by excluding features such as security and reliability. SOAP has more protocol stacked on HTTP, such as WSDL; REST does not include these features. When HTTP proves to not be useful enough, SOAP is a helpful solution. This framework is designed to be autonomous of any explicit previous style used. (SOAP, n.d.)

### IEEE P2413 – Standard for Architectural Framework for the Internet of Things (IoT)

This standard defines multiple protocol for the IoT. This includes IoT domains, compatibility of the overall system, and continuous market growth monitoring. The main goal of the IoT is expansion. (IEEE, n.d.) (IEEE, n.d.)

### WebSocket

WebSocket is an HTML standard; it is used for Web applications and communication. WebSocket is known for its communications procedure. WebSocket is usually used with TCP but can be used with UDP under certain circumstances. WebSocket also includes HTTP. This protocol allows information to be sent between two users. (Web Sockets, n.d.)

### Weave (going to use this for Beacon)

Weave aids phone-to-device-to-cloud communication. Weave helps connect to the cloud through mobile phones as well as desktop. Weave can bridge the gap of communication for device-to-device, device-to-cloud, and device-to-mobile. Weave is known for having low overhead, scalable properties, flexibility, and security even on a vulnerable network. This would be useful for Plan Bee's connection to the beacon. Being able to gain access from a mobile phone would be extremely useful in this situation as well. (WEAVE, n.d.) (WEAVE, n.d.)

## *Web Server Development*

### JSON – JavaScript Objection Notation

JSON is based off of the JavaScript programming language, however it is independent of any particular coding language. Because it has similar conventions to other languages, JSON is known for its ease of use. JSON transmits data in a way that is understandable to humans, not just a computer. Because of this, more arranged data can be conveyed. JSON usually transfers data between an application and a server. (JSON, n.d.) (What is JSON, n.d.)

### XMPP/XMPP-IOT – Extensible Messaging and Presence Protocol for Internet of Things Devices

XMPP stands for Extensible Messaging and Presence Protocol. XMPP was designed to be flexible and scalable; this is what extensible represents. XMPP also allows users to IM for communication purposes. This real-time messaging is represented by the M in XMPP. Presence in XMPP is characterized by showing other users when a user is online or offline. XMPP is a commonly used protocol that allows systems to communicate back and forth. This is another protocol used within the IoT. (XMPP, n.d.) (XMPP IoT, n.d.)

### SQL – Structured Query Language

SQL is a standard for the American National Standard Institute (ANSI) and for the International Organization for Standardization (ISO). SQL and is basically used for retrieving and editing databases. Different versions of SQL can be used depending on the specifications the user is looking for. SQL uses the Relational Database Management System to retrieve data for the user for editing. This is a useful and uncomplicated way to obtain data. (SQL, n.d.)

### NoSQL – Non SQL (Structured Query Language)

NoSQL database standards provide a mechanism for storage and retrieval of data that is modelled by means other than the tabular relations used in SQL, relational databases; it is a nonrelational database standard. It is however worth noting that SQL-like databases can exist within NoSQL databases, so NoSQL is broader, and "Not-only-SQL". There is not one way of handling data, but several, which are displayed in the figure below. (NoSQL, n.d.)

| Model | Performance | Scalability | Flexibility | Complexity | Functionality |
|---|---|---|---|---|---|
| Key-Value Store | High | High | High | None | Variable (none) |
| Column-Oriented Store | High | High | Moderate | Low | Minimal |
| Document-Oriented-Store | High | Variable-to-High | High | Low | Variable-to-Low |
| Graph Database | Variable | Variable | High | High | Graph Theory |
| Relational Database (SQL-like) | Variable | Variable | Low | Moderate | Relational Algebra |

** This data for this table was created by Ben Scofield and performance was rated for different categories of NoSQL databases using the YCSB benchmark.*

It would not be worthwhile to explore each individual method here, as whatever databasing method we use is likely going to depend upon the web host we choose, further explored in Research and Software Implementation sections. We would however prefer to use NoSQL for the flexibility it offers. (Yahoo Cloud Serving Benchmark, n.d.)

### *Front-End Web Page Development*

#### HTLM5 – Hypertext Markup Language v5 (Current)

HTML5 is a markup language for use in structuring and presenting content on the world-wide-web (WWW). It is the fifth and current version of the HTML standard. Web browsers receive HTML documents from a web-server and render the documents into structured web pages using CSS3 and JS standards, the triad of cornerstone technologies for the WWW. HTML allows the institution of constructs, images, interactive forms, text, and other web "objects". HTML also provides a means to create structured documents by denoting structural semantics of text such as headings, subheadings, paragraphs, lists, hyperlinks, quotes and other items. One of the most important features of HTML for us is the ability to hyperlink to other pages, allowing navigation on the WWW, and through our own application. (HTML5, n.d.) (MSDN, n.d.)

#### CSS3 – Cascading Style Sheets v3 (Current)

HTML5 uses CSS3 in order to "style" its pages, making them visually appealing and adding functionality. More formally, CSS it is used for describing the presentation of a document written in HTML. CSS enables us, in development of the front-end web application, to separate our presentation of content including grid, layout, colors, and fonts, improving content accessibility, providing more flexibility and control in the specification of presentation characteristics. CSS also enables multiple webpages to share the same formatting by specifying relevant (general styling) CSS in a separate ".css" file; this significantly reduces the complexity and repetition in structured content of our code. (Developing in HTML, n.d.)

### JS – JavaScript

Alongside HTML5 and CSS3, JS is one of the three core technologies that power the WWW. JS is a higher-level scripting language influenced by C (and Python) that enables functional and visual interactivity of web pages and is thusly essential for all web-based applications. As most websites on the WWW use it, all major web browsers (Firefox, Chrome, Explorer, Edge) have a JS engine to execute scripts. (JavaScript, n.d.)

JS enables support for event-driven, functional, and imperative (including object-oriented and prototype-based) programming styles, and has APIs for working with text, arrays, dates, regular variable expressions, and basic manipulation of the document-object model (DOM) for the frontend of web-based application. As it is not a server-side language (as discussed above), JS does not include any I/O, such as networking, storage, or graphics facilities, relying for these upon the host environment in which it is embedded. (Developing in HTML with JavaScript, n.d.)

## Barriers to Market Entry

### FCC Equipment Authorization for RF Devices

During prototyping, as Researchers, we are allowed to use any protocols we deem necessary to get a functional end-product we intend to use. This end product must fit within the national constraints of the FCC. Further, any RF Device that will be manufactured and produced at scale requires subjection to peer review through FCC Equipment Authorization for RF Devices, and if approved, listing within the FCC.

Our communications template device will specifically be classified as an Intentional Radiator Equipment, as it will feature an RF transmitter-receiver for the purpose of long-range communication and short-range mesh-networking. We will be using the upper-ISM bands, and our power output (in Watts) and range will be limited by regulations governing the safety of animals and individuals, exactly as we intended. Intentional Radiators are defined in Section 15.3(o) in the Electronic Code of Federal Regulations guidelines. Exemptions to Intentional Radiators are listed in 15.201 of the FCC Federal Guidelines. These devices are subject to Equipment Authorization Program by the FCC. A detailed explanation of the FCC's' Equipment Authorization Process follows.

#### *Requirements Imposed on Intentional Radiators*

Frequency ranging from 902-928 MHz Hopping shall use min of 25 kHz spacing or the 20 decibels (dB) bandwidth, whichever is greater. For less than 250 KHz bandwidths, system shall use at least 50 channels and the average time on channel shall be less than 0.4 seconds in a 50 seconds interval. (section 15.247)

There are no special testing requirements. Frequency usage should eliminate the end channels to as to not violate the bandwidth rule given above. Frequency tolerance is not specified, only that the 20 dB bandwidth shall fall inside the 902-928 MHz band. (section 15.215c)

Environmental limits are not placed on the temperature range of the operating device (intentional radiator). Power output is limited to 30 dBm max specifications, with no more than a 6 dBi antenna. Implies Ptransmitter is 30 dBm including cable loss. Spurious levels specifically state emissions outside the band shall be negative 50 dBc or less attenuation. (section 15.209)

### *Equipment Authorization Procedures*

### Legal Proceedings

#### Section 2.906 – Supplier Declaration of Conformity (SDoC)

SDoC is a procedure where the responsible party, as defined in section 2.909, makes measurements or completes other procedures found acceptable to the Commission to ensure that the equipment complies with the appropriate technical standards. Submittal to the Commission of a sample unit or representative data demonstrating compliance is not required unless specifically requested pursuant to §2.945. SDoC is applicable to all items subsequently marketed by the manufacturer, importer, or the responsible party that are identical, as defined in §2.908, to the sample tested and found acceptable by the manufacturer. The responsible party may, if it desires, apply for Certification of a device subject to the Supplier's Declaration of Conformity. In such cases, all rules governing certification will apply to that device.

#### Section 2.907 – Certification

Certification is an equipment authorization approved by the Commission or issued by a Telecommunication Certification Body (TCB) and authorized under the authority of the Commission, based on representations and test data submitted by the applicant. Certification attaches to all units subsequently marketed by the grantee which are identical (see §2.908) to the sample tested except for permissive changes or other variations authorized by the Commission pursuant to §2.1043.

#### Section 2.908 – Identical Product Already Registered

As defined by the FCC, is used in this subpart, the term identical means identical within the variation that can be expected to arise as a result of quantity production techniques.

### Approval

#### Supplier’s Declaration of Conformity (SDoC)

The responsible party, as specified in the rules, warrants that each unit of equipment complies with the applicable FCC rules. The responsible party maintains all of the required documentation demonstrating compliance with the applicable FCC rules. The responsible party prepares a compliance information statement to be supplied with the product at the time of marketing.

## Certification

The responsible party, typically the manufacturer, obtains an FCC Registration Number (FRN) for a device requiring Certification. The FRN is a 10-digit number used to identify the individual or organization doing business with the FCC. The same FRN will be used for future approvals. After obtaining an FRN, the responsible party obtains a Grantee Code from the Commission by applying at the Grantee Registration website. A grantee code is required the first time a party applies for certification and can be used for all future approvals.

The responsible party files with a Telecommunication Certification Body (TCB) an application for a grant of certification. An application for equipment authorization requires submission of information about the product, as listed in Section 2.1033. The applicant must submit the required information to a TCB for review as part of the certification process. [For a list of FCC recognized TCBs see https://apps.fcc.gov/oetcf/tcb/reports/TCBSearch.cfm]

The TCB reviews all of the supporting information and the evaluation results to determine if the product complies with the FCC requirements. Once the TCB makes a decision to certify the product the supporting information is uploaded to the FCC Equipment Authorization Electronic System (EAS) – Database. A grant of certification is issued by the TCB on the FCC Equipment Authorization Electronic System (EAS) – Database.

## Following Approval

### Label, Manual and Record Retention

The manufacturers are then to correctly label the product and provide the required customer information. The manufacturer must also maintain all documentation as part of the responsibility for the retention of records and ensure that the manufactured products are complying. For more information, see Section 2.938 – Requirements for the retention of records of equipment subject to FCC approval.

### Manufacturing, Importing and Market Approval

Changes to your product design may require an additional approval. KDB Publication 178919 gives general guidance when making changes to a previously approved product. See the permissive change rules in FCC Section 2.1043. Modifications that may be made to an RF device without filing for a new equipment authorization; Three distinct types of permissive changes; and identifies when a permissive change filing with the Commission is required.

# Design Implementation

This section includes discussion about hardware implementation, breadboard testing, schematic and block diagrams, software implementation, necessary flow charts, and hardware and software interfacing. Hardware implementation is shown through schematics of each "block" of the block diagram, and the breadboarding for each of these is also shown and discussed. Connections are then made at the PCB-design level and discussed. The software implementation is shown through discussion and flow chart, and references to the Appendix section which includes relevant code snippets – A4. The backend and frontend software interfaces and technology implementation are also shown and discussed.

## Hardware

### Device Schematic Details

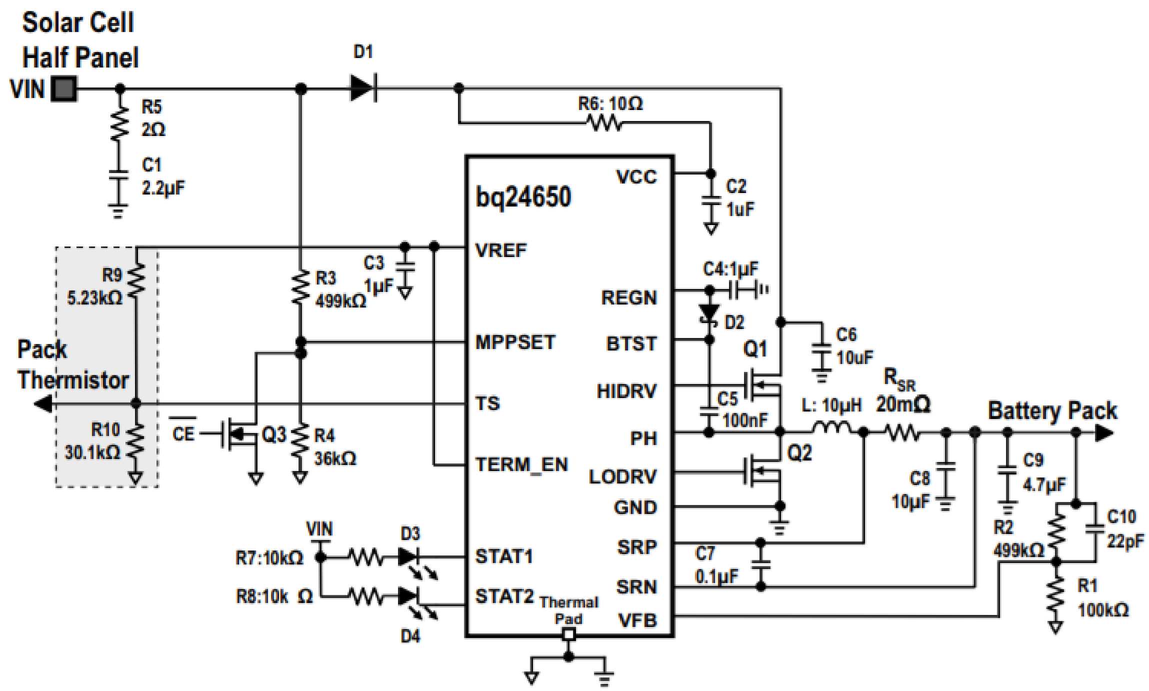
#### *Summary*

This section features recommended device implementation details. We recount the manufacturer reasoning behind their implementations and discuss how such implementation details will be integrated into our final project. The overall design and implementation of the circuit will be done using Altium Designer. This program is easy to work with and extremely useful for PCB design. Plan Bee needs to focus on maintaining a seamless PCB design. This includes things such as making sure all components are of the same mount type (surface mount), as well as creating the most efficient design. This includes placing components in the easiest to work with and useful manner. By practicing these concepts, many of the schematics below have been created.

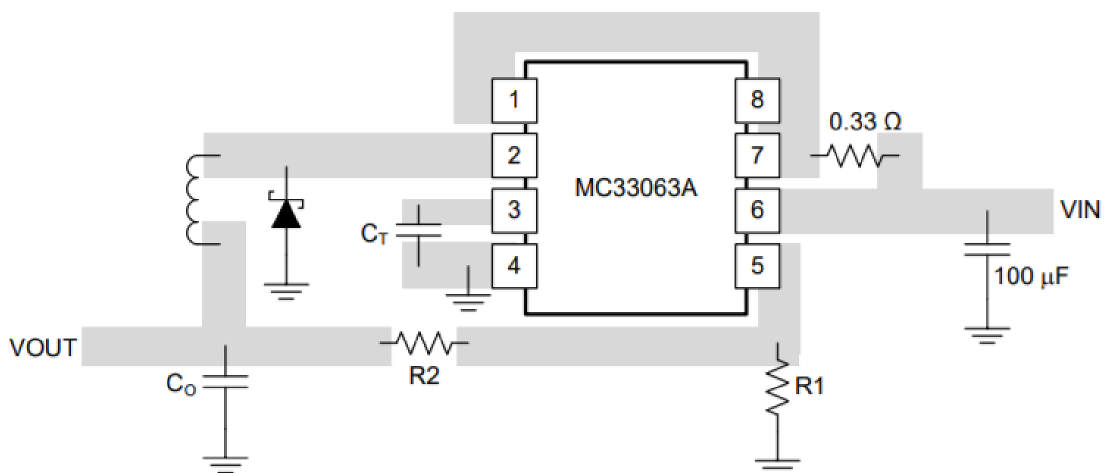
#### *Power*

##### BQ24650RVAT

The BQ4650RVAT comes designed to effectively provide DC power by having an entry side that cuts out any alternating signal. It also comes with a thermistor to help sense its temperature besides the circuitry necessary for proper feedback for the MPPT system and battery level feedback system.




### MC33063ADR

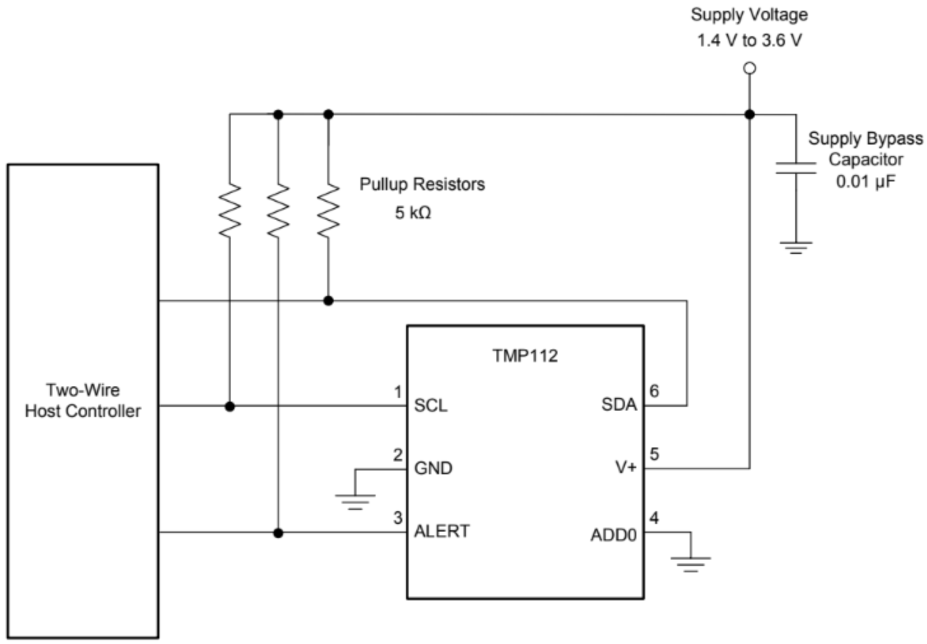



## *Sensors*

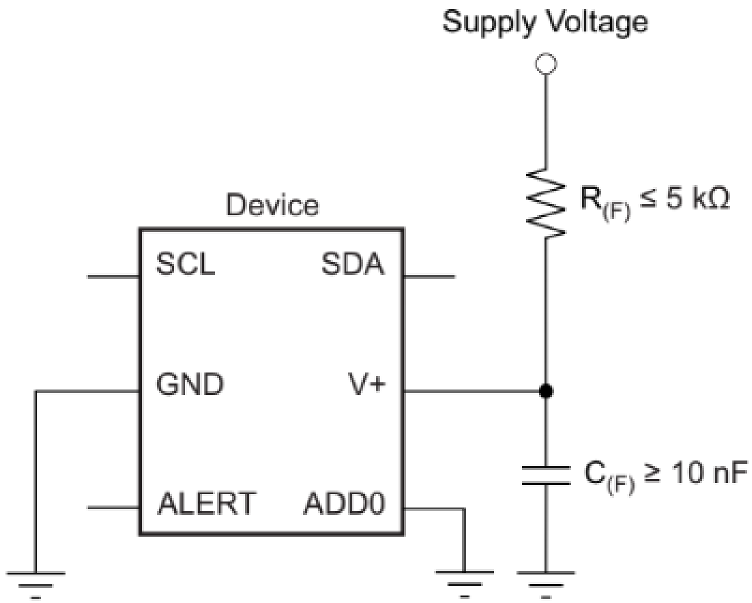
### TMP112

Because the TMP112 is a temperature sensor, making sure to alert the owner of temperature abnormalities is a requirement. This has been looked at by Plan Bee when considering board selection. The TMP112 temperature sensor has certain schematic configurations that increase its productivity and efficiency. This includes noise reduction configurations, filters, and required pullup resistors. Knowing what components are required for the TMP112 as well as what configurations help increase the sensor's abilities will help Plan Bee with the design and implementation of a PCB schematic that includes this chip.

The TMP112 needs pullup resistors on three pins; a value of around 5kΩ should be used for the SCL, SDA, and ALERT pins. This recommendation is for preventing the current from surpassing 3 mA at any of these three pins. A capacitor of .01µF can also be used as a bypass on the supply voltage. This capacitor should be placed near as possible to the supply and ground pins. This recommended design is shown below.

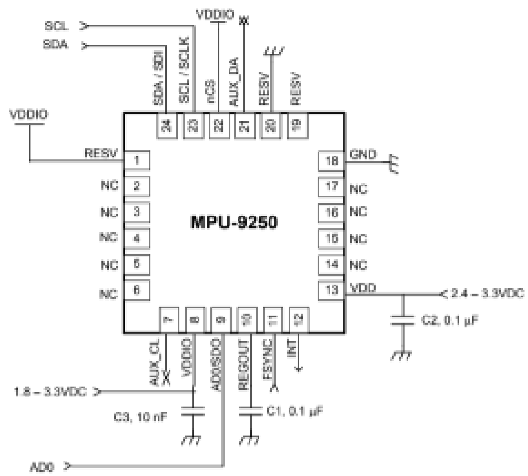


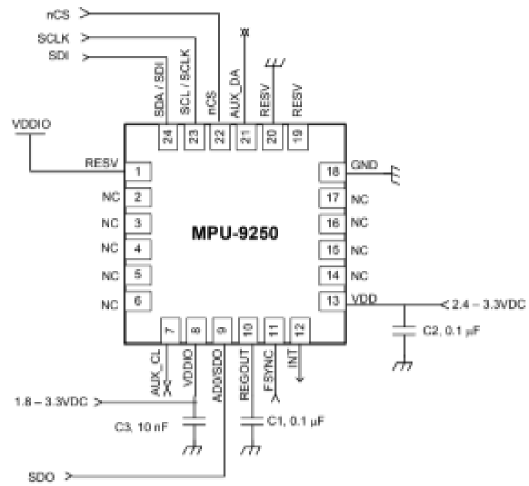

The TMP112 usually doesn't generate much noise, partly because of how little power it needs to run. However, if the power source has a high impedance, noise will be more likely to occur. Plan Bee is choosing a power source after choosing all other components that requiring power; this is to ensure a proper decision is made on how much power, voltage, and current are truly needed throughout the prototype device. Because of this, it would be safest to apply noise reduction techniques to the schematic including the TMP112. This will ensure as little noise as possible, even if the impedance from the power supply is higher than expected. One of the simplest noise reduction techniques would be an RC filter. This would include adding a resistor connecting from the supply voltage to the V+ node, while also adding a capacitor to the same V+ node. This capacitor would also be connected to ground. This noise reduction technique is shown in the schematic below. For this technique to truly be effective, the resistor value should fall below 5k, and the capacitor value should be above 10nF. These general component additions could help increase the abilities of the TMP112 sensor in Plan Bee's design. Implementing them into the PCB schematic is useful for preventative measures.



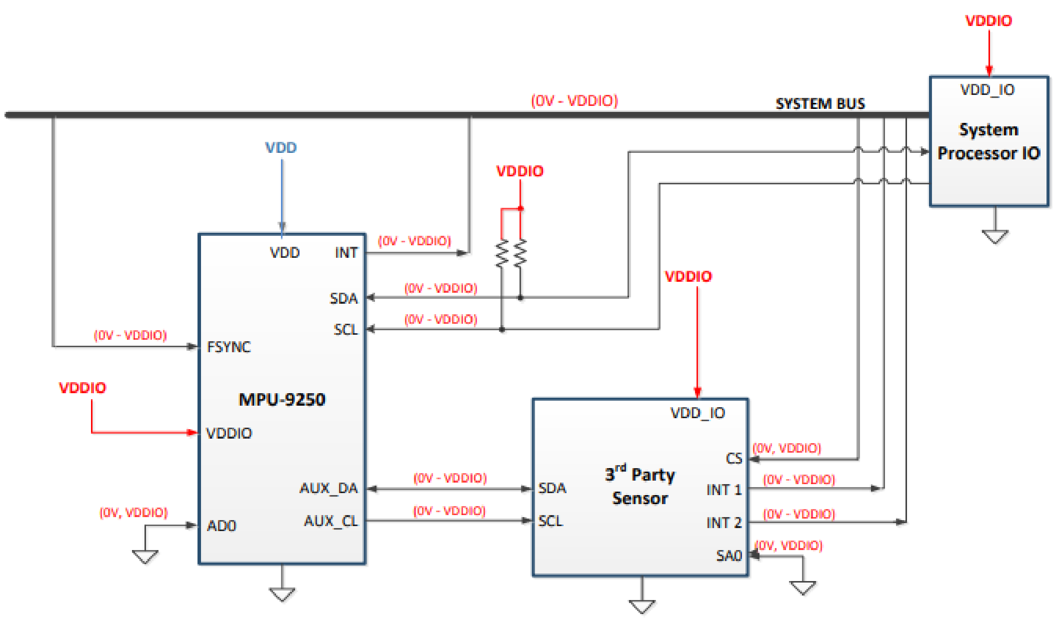

## MPU9250

The MPU-9250 has twenty-four pins. Because the MPU can operate with I$^2$C and with SPI, there are different configurations that can be made for each interface. Capacitors would be placed at the same three pins regardless of which interface type is being used. REGOUT and VDD should have a .1µF capacitor that is also connected to ground; whereas VDDIO should have the same configuration, except the capacitor should be 10nF. The two .1µF capacitors would act as bypass capacitors and the 10nF capacitor would be a regulator filter capacitor. These three components are the main required exterior components for this sensor chip. There are two main differences between the I$^2$C and the SPI operation configurations, which are shown in the figure below. ￼ configuration is the left picture, whereas SPI is on the right. For ￼, the ninth pin is the AD0 pin, whereas for SPI it is the SDO pin. Another dissimilarity like this one occurs at pins twenty-three and twenty-four. Pin twenty-three is labeled SCL for ￼ and SCLK for SPI. For pin twenty-four, the I$^2$C operation configuration is SDA; SPI is SDI for pin twenty-four. The nCS pin (pin twenty-two) is connected to VDDIO under the I$^2$C operation, but this is not recommended for the SPI arrangement.



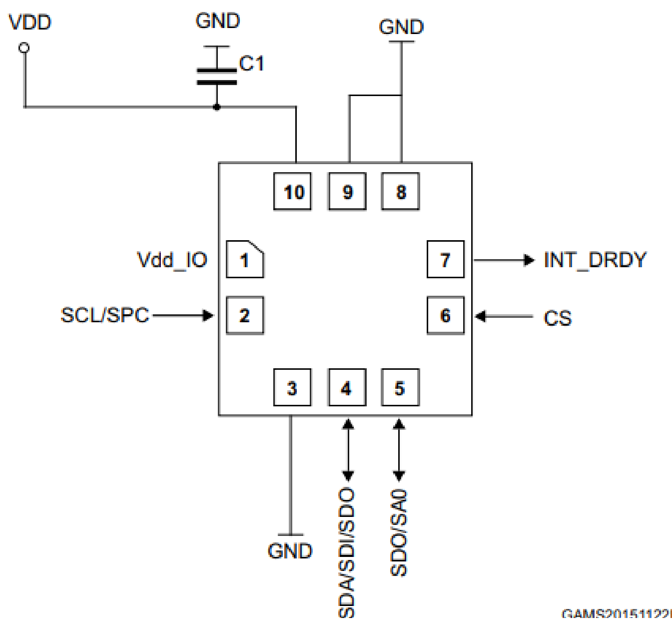




Other sensors can be attached to the MPU-9250 chip. Common configurations are important for Plan Bee to understand so the schematic creation process for this sensor can be as streamlined as possible. The MPU-9250 would primarily run with $I^2C$ interface for this project; the connection of another sensor to the MPU-9250 would be through the auxiliary $I^2C$ bus. The system processor would link to the SDA and SCL pins; these connected wires would include pullup resistors as well. Pin configurations for this schematic design are important as well. Pins such as FSYNC, SDA, SCL, INT, and AD0 are all connected to VDDIO. The other sensor, that would need to be designed in a schematic on a case by case basis, would still be connected to VDDIO and MPU-9250 as well. This configuration is shown below, and although it is useful for basic schematic designing, it will need to be altered to fit the specific needs of this project.




## LPS22HB

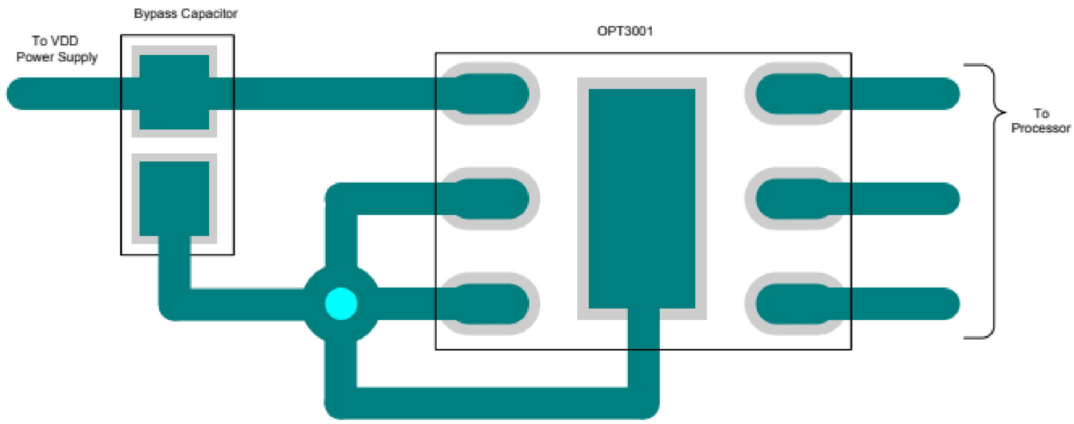
The LPS22HB has ten pins, much more manageable than the MPU-9250's twenty-four. Because this sensor is less complex, the schematic design surrounding this chip will be simpler as well. This chip can also use two different interfaces, $I^2C$ and SPI. Pin two is dual configured for either SCL (for $I^2C$) or SPC (for SPI). Pin four has a similar situation, with $I^2C$ configuration represented by SDA and SPI by SDI. The same type of $I^2C$/SPI pin differences apply to pin five as well, changing from SD0 to SAO, respectively. VDD is pin ten and has a 100nF capacitor attached as a bypass. This capacitor is recommended to be as close as possible to the supply pads of the device. This basic configuration is the start to designing this part of the PCB schematic. The figure below showcases this design.




## OPT3001

Much like the TMP112, The OPT3001's readings are also greatly affected by its surroundings on the board. Things that are especially reflective and can affect light, especially light that can be seen by the human eye, will greatly affect the measurements this sensor helps record. Taking special care to place surrounding components that fall into this category either above the sensor or away from the sensor is of upmost importance. This is a main concern when considering PCB layouts for this project.

Another recommendation is to include a bypass capacitor from the power supply going to this chip. The capacitor should be placed near the OPT3001. Making sure any light reflected from the capacitor does not reach the OPT3001 is very important. Having the capacitor raised to double the height of the OPT3001 would help this but may be difficult to accomplish. It is also recommended to connect the thermal pad of the OPT3001 to ground electronically through the board. A PCB trace would be the easiest way to do this and could be implemented in Altium. A PCB layout of this is shown below.




Because Plan Bee will most likely have the PCB board enclosed in protective casing, it is helpful to get an understanding on how to help make this chip most effective through casing and behind a dark window. There are examples of this schematic design, which include adding resistors between the VDD node and the SCL, SDA, and INT pins. This example is illustrated below. A capacitor is also applied at VDD and grounded. This setup would provide well for diverse conditions but would need to be tested thoroughly to ensure the OPT3001 is still providing useful and accurate information.

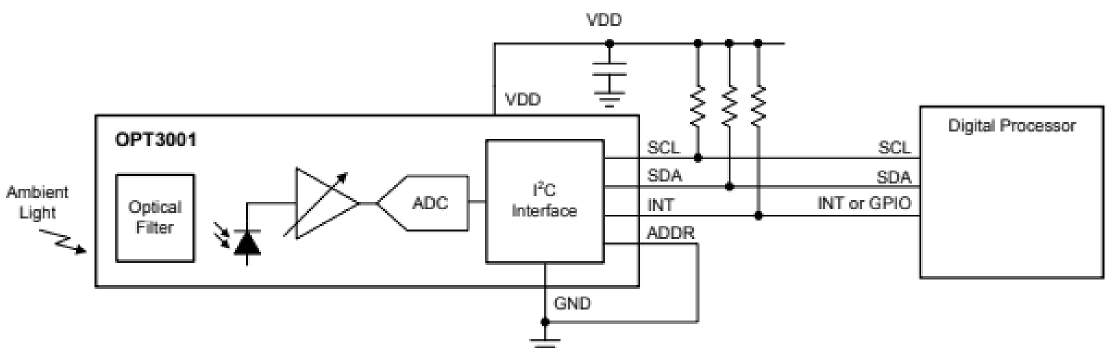
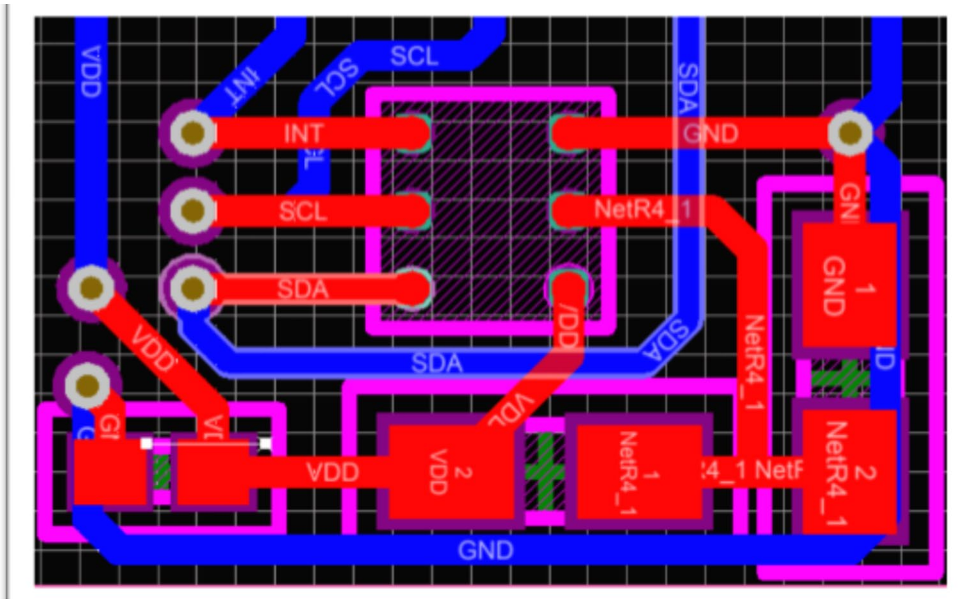



*Figure 4 HDC2010 Reference Implementation*

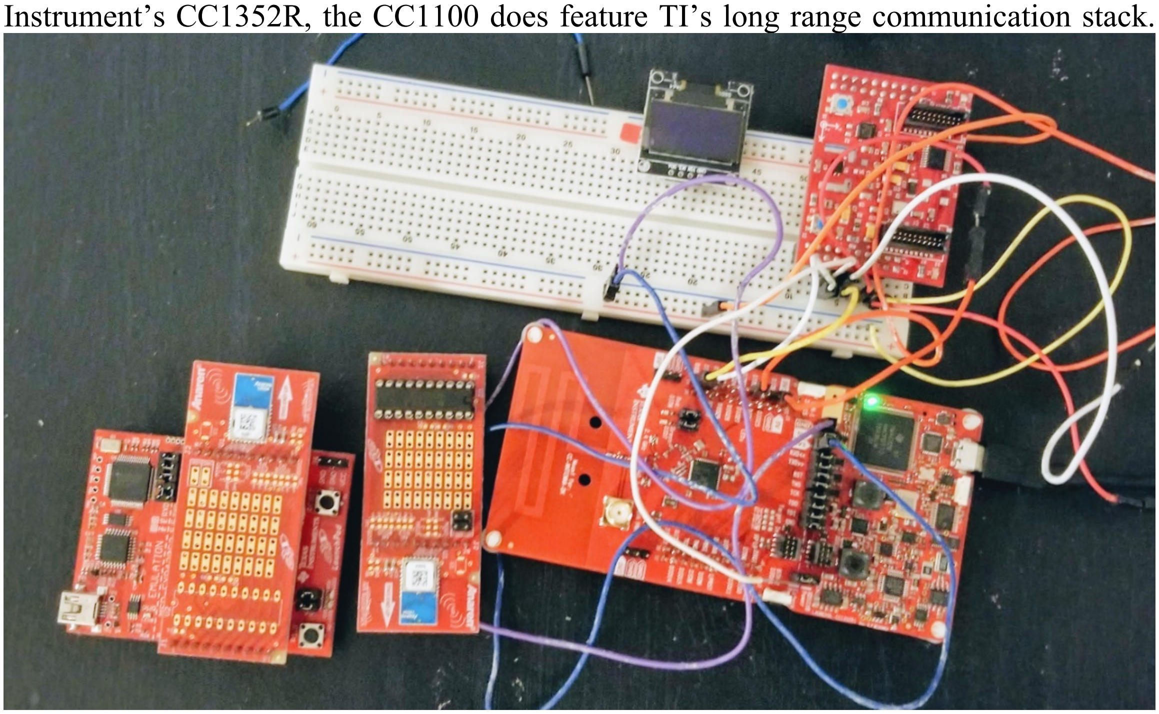
## HDC2010

To enhance thermal isolation, a slot should be made in the PCB for the HDC2010 to be laid. To maintain this thermal isolation, the only component that should be near the HDC2010 should be a bypass capacitor that is along the same wire as the voltage supply source. This bypass capacitor between VDD and ground is recommended to be multilayer and ceramic to prevent any heat from affecting the nearby sensor. The HDC2010 should be further away from any other components, preventing the heat they generate from affecting the accuracy of this chip. The slot in the PCB will increase the accuracy as much as possible and prevent the sensor from any slight environmental wear and tear or heat exposure that may occur. This setup is shown in the PCB schematic below.




## Breadboard Testing

This section reviews the application and methods used to test the various parameters encompassing the project. Initially, Texas Instruments CC1100 was used to testing low powered wide are network range. This was done using a custom application built by a company called Anaren. This application is able to send temperature data across 2 MSP430 using a Texas Insturment CC1100 wireless transceiver. While not as powerful as Texas Instrument's CC1352R, the CC1100 does feature TI's long range communication stack.



As such, the distance of communication has been touted to be capable of reaching 10 kilometers. The CC1100 development boards were flash with Anarens default application and asserted o be able to wirelessly communicate at short distances. One of the boards was then moved until communication halted. A range of approximately 50 ft was also recorded. Such an experiment leads us to further inspect the possibilities of choosing a alternate long range communication device. We happily sided with Texas Instruments CC1352R due to the additional gain promoted. Two development boards were purchased, and one attached to a breadboard in order to test Texas Instruments' sensor hub booster pack. This booster pack houses numerous sensor devices and is easily interfaced with the CC1352R development board using the I2C port. The following section goes into detail on the testing methodologies.

*Figure 5 Photograph of BreadBoard Testing*

Sensors utilizing $I^2C$ were purposefully chosen primarily for the ease of use and expandability. $I^2C$ provides a robust method of communicating with many devices and allows additional devices to be incorporated in a preexisting design. Such an architecture allows the primary microcontroller to communicate with as much as 128 different devices. The Sensor Hub Booster Pack, designed by Texas Instruments, was used to test $I^2C$ communication and sensory data acquisition. The Sensor Hub features an MPU9150 by Invensense; this device integrates a 3-axis gyro, 3-axis accelerometer, 3-axis compass and a temperature sensor in to a single device. Additionally, the Sensor Hub Booster Pack Features Bosh Sensortec BMP180 pressure sensor, Sensirion SHT21 humidity sensor and ambient temperature sensor, an Intersil IS2903 ambient and infra-red-light sensor and Texas Instruments TMP006 non-contact infrared temperature sensor. Because this board was developed for Texas Instruments Tiva-C model processers, the headers were not pin compatible with the CC1352R development board. As a result, the device was modified, and its signals made available by attaching it to a breadboard. The necessary routings were then made between the CC1352 development board and the sensor hub.

To test communication and sensor data Texas Instruments Sensor Controller Studio was used. This application compiles code specifically designed for sensor devices, for the ARM thumb auxiliary micro controller integrated in the CC1352R. The sensor controller features a low powered ARM module fitting for communication polling transducers and other types of sensory devices. Communication is handled using semaphores between the main controller and sensor controller. This reduces power consumption and allocates computer time to the main controller. Code was then created to drive the listed sensors and the data was collected and reviewed. To aid with serial communication and logic analyzer was used to scan the $I^2C$ bus. Sniffing the bus allowed us to assert the accuracy of the data being communicated between devices. Below we provide the result of each sensor that had been tested.

### Invensense MPU9150

The Invensense MPU9150 documentation provided the needed information necessary to initialize the sensor and read its data. The MPU9150 follows a similar implementation pattern as our final device, MPU9250. As a result, testing such a device will follow a similar vein as the final motion sensor. The initializing process for Invensense MPU9150 relies on power cycling the chip and waking it from sleep. From then the chip goes through a self-diagnosis stage were by it reads factory data and tries to calibrate its various sensors against a control system. The MPU9150 also features an interrupt line which is able to interrupt the master controller on specified programmed events. This feature, in addition to polling the system at 200 hertz was enabled. This code used to initiate and drive this device was developed using Sensor Controller Studio and will be integrated into the final project. The sensor data of the MPU9150 is stored in multiple internal registers. Each sensor was able to provide a 16 bits value which was stored in 2 consecutive 8-bit addresses. To access the address the MPU9150's $I^2C$ address, 0x68, was first placed on the bus, followed by a series of instructions and a final read with acknowledge value. The diagram below presents the $I^2C$ bus as data was transmitted. As one could see, the main address was first placed on the bus, followed by additional the register to read and a read with acknowledge bit for each register value.

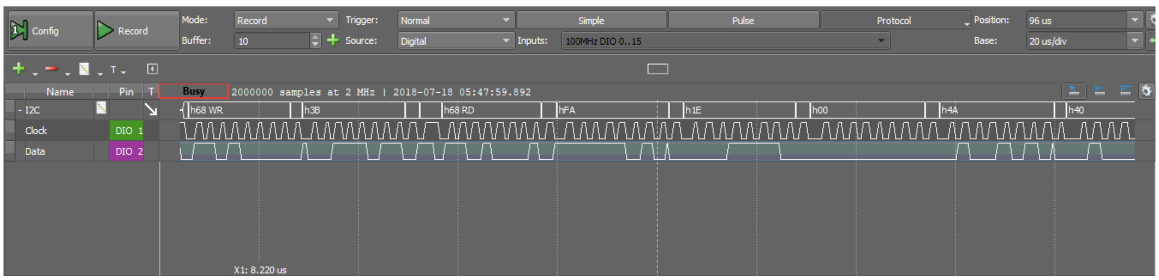



*Figure 6 I2C Accelerometer Stream, recorded using logic analyzer*

In addition to the communication testing, the data transmitted across the $I^2C$ bus was also tested and graphed against time. Force was placed on the accelerometer and the change acceleration was graphed accordingly; this is presented in the figure 11, below.

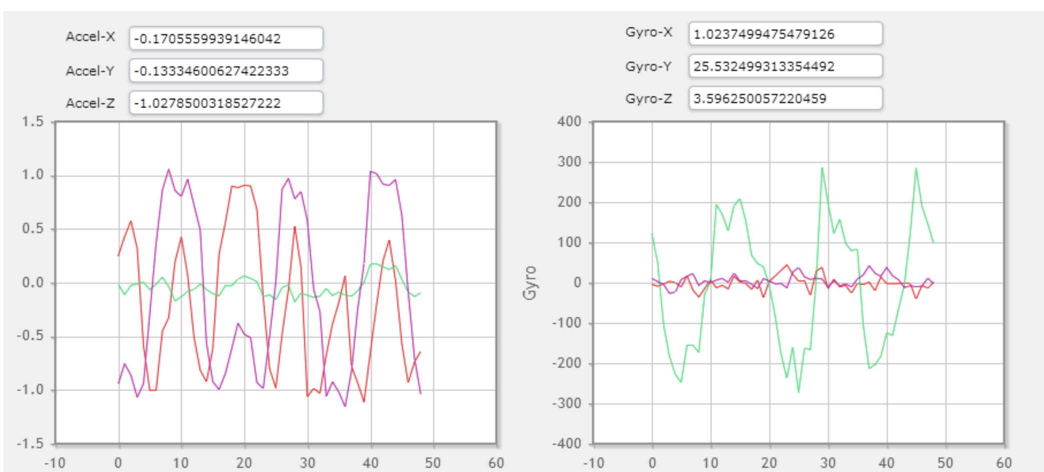



*Figure 7 Accelerometer and Gyroscope Testing*

Similarly, the gyroscope measured the centripetal speed of the sensor hub. The data gathered form the gyroscope against a period was is shown in figure 12. As the development board was moved the graph adjusted accordingly. The compass of the MPU9150 has been relegated to a secondary $I^2C$ device. As such it utilizes a separate address from that of the main MPU9150. As a result, separate code was made to manage the compass. Like the MPU9150, data was read by applying a device address to the $I^2C$

bus followed by a starting register address. A read with acknowledge instruction was the pass to the bus to read the necessary data. The figure above showcases compass data read form the MPU9150. As the development device was altered the compass also changed. While such data needed to be calibrated, the values and changes in values are significant testing blocks for the final application.

[TODO: accelerometer, compass Graphics]

### *Sensirion SHT21*

Sensirion's SHT21 integrates a capacitive humidity and temperature sensor. The humidity sensor is able to decipher humidity reading with a resolution of up to 14-bits. This chip is integrated with TI's sensor-hub booster module. As a result, to test this sensor the sensor-hub I2C connector was attached to the CC1352R development board. Like the accelerometer, Texas Instruments' sensor controller studio was used to query the data from the chip. The chip was first initialized as described in the datasheets. A logic analyzer was used to validate the initialization process. After initialization, the chip was then queried for humidity data. The SHT21 transmits data across 2 bytes packages; with the MSB transferred first. Each byte is followed by an acknowledgement. The transferred 16 bits of data comprises of a 14-bit value which represents the final raw data and a 2 bit status value. The raw data was queried over time and the data graphed using Texas Instruments' sensor controller studio. The Image below showcases the captured humidity sensor data plotted against time. As shown the data remained a constant value of 24524 as the humidity in the room remained constant.

[TODO: Humidity sensor graph]

The relative humidity value could be calculated using the formula specified in the datasheet. That is;

$$Relative\ humdity = -6 + 125 * \frac{RawValue}{2^{16}}$$

## RF Testing

### *Long Range Communication Testing*

To rapidly prototype wireless communication, Texas Instruments' SmartRF software tools was used to configure the RF transceiver to communication across various parameters and also transmit an arbitrary set of data across differing ranges. SmartRF allows rapid application testing and can provide additional features such as wireless sniffing and wireless integration techniques using various wireless standards such as Bluetooth and Zigbee. To begin, a CC1352R development board was attached to a computer using USB. The devices was then activated in the SmartRF software and its features queried for transferring data. SmartRF offers a set of configuration options which presents an assorted amount of communication method to be used for communication. To test the long-range communication, the SimpleLink long range communication configuration was used.

*Figure 8 Communication Range 523 meters*

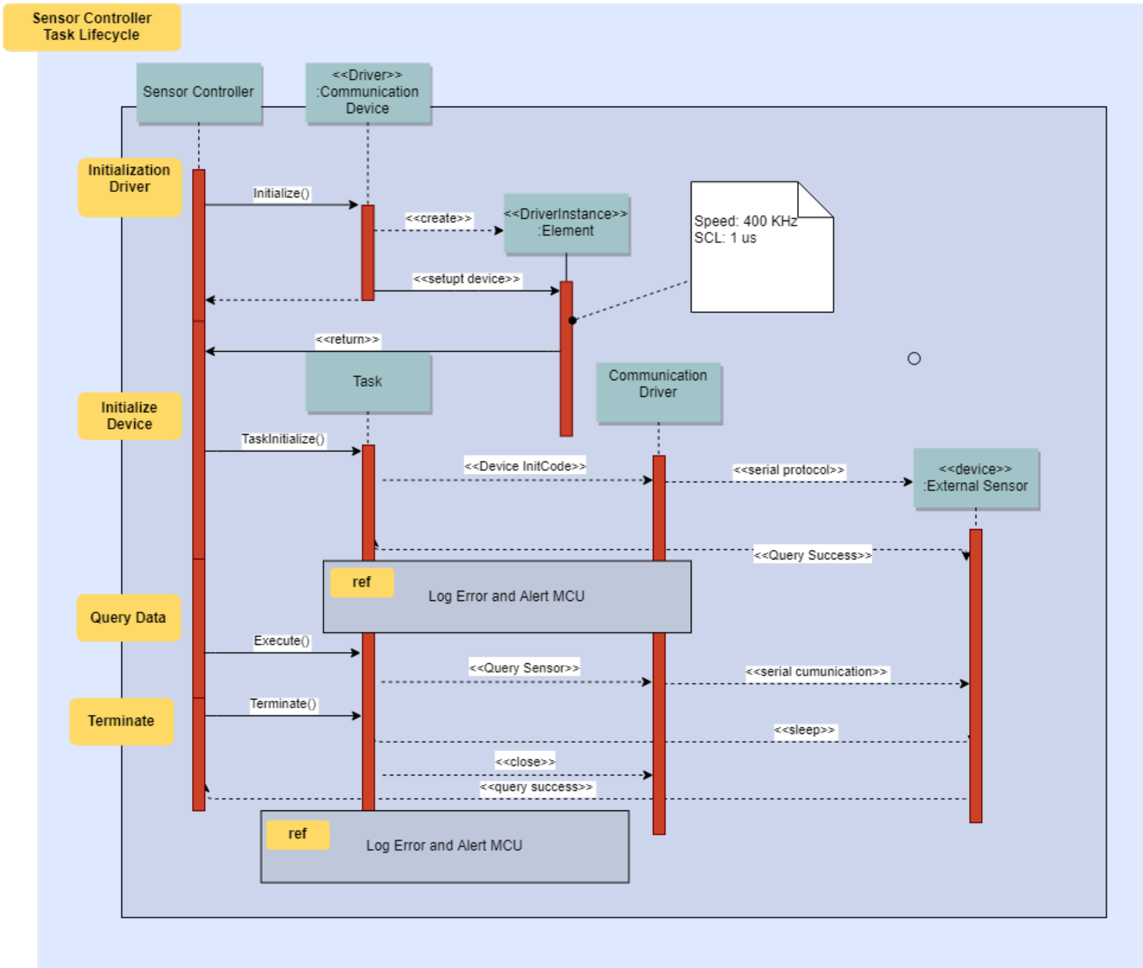
A variable length data packed comprised of randomly generated data was then created. The packet consisted of an initial 16-bit preamble followed by a 32-bit sync word. This is then followed by a 8-bit length value, then an 8-bit address value and finally the variable length data. Another CC1352R development board was attached to a second computer and the receive option was selected in SmartRF. This selection option was matched with that of the transferring board and the reception was initiated. The reception device presented the packet data as generated by the transferring device. To test overall reception distance, the transfer method was set to continuous and the device on the receiving end was relocated. Given the transferring device was elevated 12 feet above ground, an estimated communication distance of about 1500 feet was achieved. While this distance was significantly less than what is proposed, we do believe the distance could be improved by installing a better antenna and utilizing more power. In addition, the test took place in a moving vehicle within a rural environment. Both of which would have an adverse affect on the final operating distance. Further testing will be done to achieve a greater distance. Texas Instrument has also promoted their CC1352P; this chip features a higher power wireless transceiver and is also pin compatible with currently selected CC1352R. While the chip is not yet available; when it is, I do believe migration will be drastically simplified because of application abstraction made possible with Texas Instruments' RTOS.

## Overall Schematic

## Software Design Details

### Firmware

*Low Powered Sensor Controller*




The CC1352 incorporates an ultra-low powered ARM processor used for acquiring sensory data. This data is then shared with a task running on the main MCU using memory controlling elements. To execute code directly on the sensor controller; an application would be precompiled and integrated within the main program code. During execution the main processor transfers the compiled application binary to a memory mapped location, where the sensor application would be initialized to execute the code at the specified address. A sensor controller application utilizes a basic scheduler to manage a set of application processes. These processes are consigned to acquire sensory data form the external devices connected through UART, SPI or $I^2C$. When initialized, each task passes through a specific application lifecycle where it is responsible for managing memory allocation, and deallocation; application drivers; and passing data from the sensor controller to the main controller. The stages of the application lifecycle involve an initialization stage; execution stage; and termination stage.

The sensor controller would periodically wake from a sleep state and go through each stage before going back to sleep. This allows the CC1352 to utilize significantly little power; on the order of 0.08 micro-amps. This not only minimizes power consumption but also relegates more pressing task to the main micro-controller unit. For $I^2C$ devices, the initialization stage involves setting up the $I^2C$ bus. The bus is initialized with a frequency of 400 kilo-hertz and a stretch timeout of 1 microsecond. The $I^2C$ communication is also setup to support 8-bit bus communication. After initializing the communication protocol, the sensor controller module then initializes the specific devices to be queried. This is done using device specific code and relies on the sensor controller sending initialization command across $I^2C$ bus. After the initialization stage, the sensor controller then queries the necessary data from the device. If the received data was returned corrupted, or communication was hindered during this stage, the sensor controller logs a communication error with the main controller and then continues to the next process. The troubled process will be return to on the proceeding cycle and the number of attempts logged. If data is acquired successfully, the sensor controller stores the output data in a special memory address where it could be accessed by the main controller. The sensor controller then closes the initialized buffers and drivers before proceeding to the next task in the task queue.

### *Main Application Framework*

Texas Instruments' TI-RTOS provides a robust application programming interface which is usually matched with their many testing tools and helper programs. The embedded kernel features task scheduling, memory management and protection using semaphores, and interrupt management. A task consist of a memory stack, heap location and is also assigned a task priority. Task are also divided into 4 types. Hadware interrupts (HWI), software interrupt (SWI), application task, and idle task. The types are also prioritized where HWI has the leading priority. Hardware Interrupt Tasks (HWI) are specifically used to manage hardware interrupts created form external devices and are therefore blocking. The scheduler executes task depending on their type and priority.

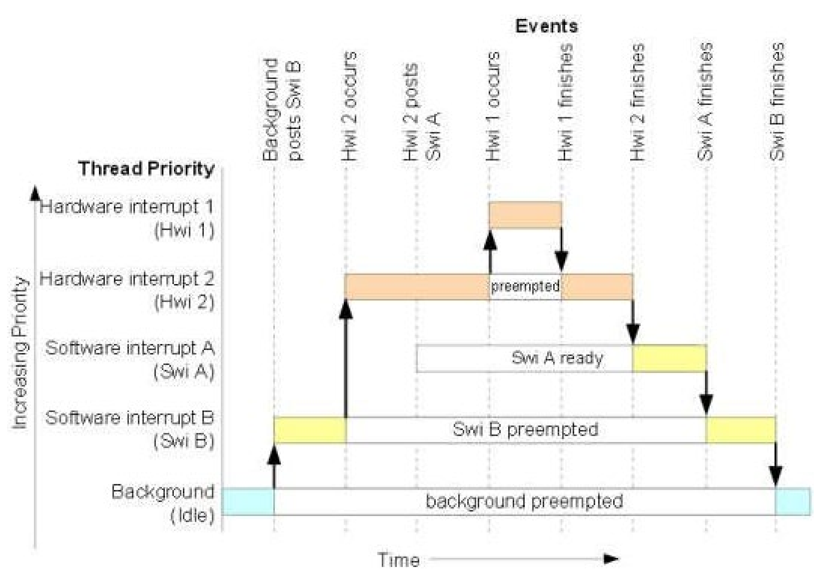
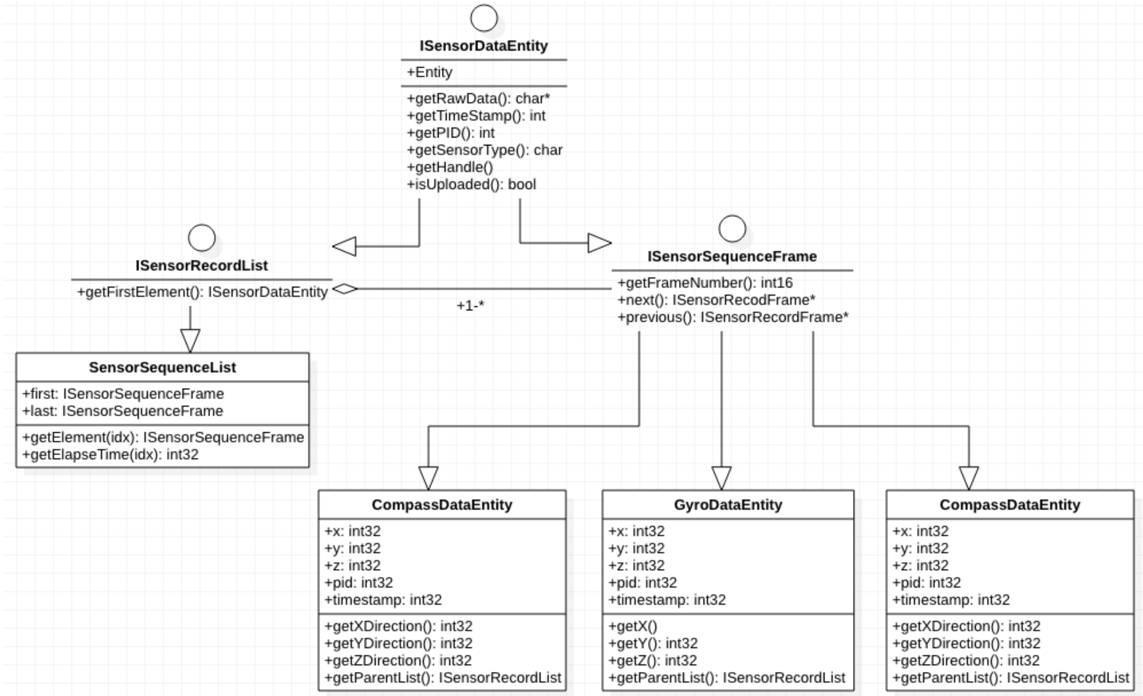



*Figure 9 Software and Hardware Interrupting Schemes*

## Firmware Class Diagrams

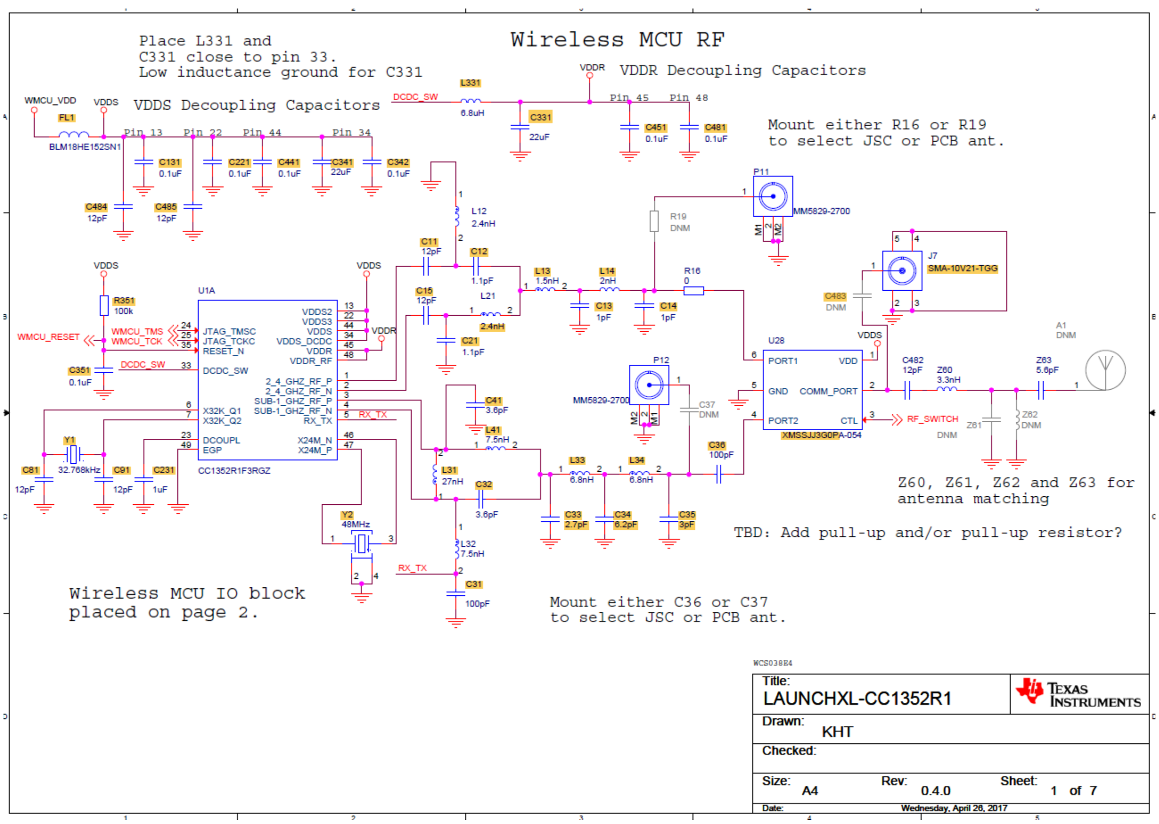


# Integration

This section includes overall integration, PCB design, and system testing information. This includes both software and hardware integration. Firmware and drivers integrated under the same "roof" of software are considered overall software integration, and will be shown and explained in detail, as well as referenced to the Appendix with relevant code. The Major PCB Design, including the Power, RF and Communications, and sensors cluster inputs will be shown and explained in detail. Testing pads will be available throughout the finalized PCB, and system testing will be done when this our PCB has completed fabrication.

[TODO: overall integration, PCB Design and system testing]

## RF Schematic



### Firmware

[TODO: Description here...]

## Administration

This section discusses implementation costs and membership responsibilities. Member responsibilities includes a breakdown of the technologies present within our end-product, and who is expected to be responsible for those technologies. Milestones includes a week-by-week listing of deliverables, and who is doing them, until the very end of senior design II, in order to realize our project in a timely and efficient manner. Under implementation cost, we have included an initial budget. This is an initial budget and by no means final but is also an overestimate in order to accommodate any unexpected expenses in our projections. Financials also includes Running Tabulations, which will include receipts from all parts ordered and any associated project costs to the sponsor, as well as a running tabulation from these receipts of how much of our budget we have spent. At the end of senior design II, we will request at least three (3) quotes from different manufacturers for our end-product in full implementation – at least one of these must feasibly remain under $70 to meet our product design constraints discussed in the Constraints section. *This section is subject to updates and change consistently, as we progress.*

### Member Responsibilities

The diagram below shows our initial team member responsibilities. Software development will largely fall into the responsibilities of Yannick Roberts. Tariq Ausaf will be responsible for some software design and implementation, but more so the major PCB design, RF Communications, and the LPWAN Gateway. Giovanny Reyes will be responsible for power delivery applications and assisting Tariq in PCB design. Katelyn Winters will be responsible for web application development and a large segment of software development with Yannick Roberts.

| Technology-in-Development | Primary | Secondary |
|---|---|---|
| Firmware | Yannick Roberts | Tariq Ausaf |
| Server | Yannick Roberts | Katelyn Winters |
| Back-End | Yannick Roberts | Katelyn Winters |
| Web Application | Yannick Roberts | Tariq Ausaf |
| Design (Beautification) | Katelyn Winters | Yannick Roberts |
| PCB (RF) | Tariq Ausaf | Giovanny Reyes |
| PCB (Weight Sensors) | Tariq Ausaf | Katelyn Winters |
| PCB (SAW Sensors) | Tariq Ausaf | Katelyn Winters |
| PCB (Internal Sensors) | Tariq Ausaf | Giovanny Reyes |
| PCB (Power) | Giovanny Reyes | Tariq Ausaf |
| PCB (Storage) | Giovanny Reyes | Tariq Ausaf |
| PCB (Interfacing) | Tariq Ausaf | Yannick Roberts |
| LPWAN Gateway | Yannick Roberts | Giovanny Reyes |

| | | |
|---|---|---|
| **Bluetooth** | Tariq Ausaf | Giovanny Reyes |
| **Zigbee** | Giovanny Reyes | Tariq Ausaf |

## Milestones

In this section we present a set of smaller, week-by-week deliverables that we can feasibly accomplish together, in order to make significant progress toward the end goal of completed our senior design project by November. Although our senior design presentation will not be until mid-December, we would like to have our project completed in sufficient time for ample testing; and in case we lag behind the agenda presented here, we will have scheduled time to recuperate. The current week is bolded to stand out, showcasing what we have accomplished thus far, and what we still have ahead of us. Two milestone-important weeks have been bolded and italicized; the first being the week we should have the project completed by, and the second being the week in which we are expecting to present our project.

| Week No. | Dates | Milestone Deliverables |
|---|---|---|
| 1 | 5/13 - 5/19 | Senior Design Group Formed. Preliminary Project Idea Submitted on 5/18 @ 12 pm. Purchased Senior Design Books. |
| 2 | 5/20 – 5/26 | Received TI MSP430 Microcontroller. Received TI Sensors Booster Pack Plug-In Module. |
| 3 | 5/27 – 6/3 | Received TI MSP430-EXP430G2 Microcontroller for Comms. Interfacing.<br>Received TI CC1300x Ultra-Low Power Wireless MCU. Ordered TI CC1352R Simple Link Ultra-Low Power Dual-Band Wireless MCU. |
| 4 | 6/3 – 6/9 | **10-Page Initial Project Documentation (Divide & Conquer) Submitted on 6/8 @ 12 pm.** Preliminary Prototyping Work Completed on Temperature Sensor. |
| 5 | 6/10 – 6/16 | **First Meeting with Dr. Lei Wei, Dr. Ritchie on 6/13 @ 2 pm. Updated 10-Page Initial Project Doc. Submitted on 6/15 @ 12 pm.** Group became Familiar working with MSP430-EXP430G2, CC1300x MCU, and the sensors module and began initial coding. |
| 6 | 6/17 – 6/23 | 15 pages of Group Contributions to 60-Page Documentation. Began estimation and ordering of parts needed for functional power requirements. Began a specific parts list and itemized (continuous) budget. Ordered Load Cells. Setup CC1300x for Bluetooth Comm., setup sensors module to track vibrations from accelerometer, humidity from humidity sensor, and temperature from temperature sensor. |
| 7 | 6/24 – 6/30 | 20 pages of Group Contributions to 60-Page Documentation. Became familiar with common ASM pheromone sensors, vibration sensors specifications for measuring beehive communications and density of the hive. Began experimenting with load cells. |

| | | |
|---|---|---|
| 8 | 7/1 – 7/7 | 15 pages of Group Contributions to 60-Page Documentation. **Second meeting with Dr. Lei Wei and Dr. Ritchie on 7/2 @ 2 pm. 60-Page Draft of Final SD1 Documentation Submitted by 7/6 @ 12 pm.** Begin integration of Load cells into prototype MCU. |
| 9 | 7/8 – 7/14 | 25 pages of Group Contributions to 100-Page Documentation. Order more sensors (vibration sensors, ASM sensor parts, others). Continue integration of Load cells into prototype MCU. |
| 10 | 7/15 – 7/21 | 15 pages of Group Contributions to 100-Page Documentation. **100-Page Draft SD1 Documentation due 6/20 @ 12 pm.** Begin integrating sensors into prototype MCU. Begin major PCB design. |
| 11 | 7/22 – 7/28 | 15 pages of Group Contributions to 120-Page Documentation. Begin adding sensors support to PCB design. Integrate pheromone sensors using ASM into prototype MCU. |
| 12 | 7/29 – 8/4 | 15 pages of Group Contributions to 120-Page Documentation. (Over) **120-Page Final SD1 Documentation due 7/28 @ 12 pm.** Finish and order first PCB. |
| 13 | 8/5 – 8/11 | Summer-Fall Break |
| 14 | 8/12 – 8/18 | Summer-Fall Break |
| 15 | 8/29 – 8/25 | Updates to Senior Design Project Documentation. Finish testing first PCB. Redesign components for second PCB. Setup Amazon AWS for server usage. Begin server-side software development. Begin application development. |
| 16 | 8/26 – 9/1 | Updates to Senior Design Project Documentation. Begin integrating new any new components into second PCB. Continue work on server-side software development and application development. |
| 17 | 9/2 – 9/8 | Updates to Senior Design Project Documentation. Complete and order second PCB. Continue work on server-side software development and application development. |
| 18 | 9/9 – 9/15 | Updates to Senior Design Project Documentation. Continue work on server-side software development and application development. |
| 19 | 9/16 – 9/22 | Updates to Senior Design Project Documentation. Continue work on server-side software development and application development. |
| 20 | 9/23 – 9/29 | Updates to Senior Design Project Documentation. Finish testing second PCB. If necessary, begin iteration for third (and final) PCB design, and have testing done in the first week of November. Continue work on server-side software development and application development. |
| 21 | 9/30 – 10/6 | Updates to Senior Design Project Documentation. Continue work on server-side software development and application development. |
| 22 | 10/7 – 10/13 | Updates to Senior Design Project Documentation. Continue work on server-side software development and application development. |

| | | |
|---|---|---|
| 23 | 10/14 – 10/20 | Updates to Senior Design Project Documentation. Continue work on server-side software development and application development. |
| 24 | 10/21 – 10/27 | Updates to Senior Design Project Documentation. Continue work on server-side software development and application development. |
| 25 | 10/28 – 11/3 | Updates to Senior Design Project Documentation. Continue work on server-side software development and application development. Have Senior Design Project Completed. |
| 26 | 11/4 – 11/10 | Begin Applicable field testing. Begin writing User Manual Section of Senior Design Documentation. |
| 27 | 11/11 – 11/17 | Continue Applicable Field Testing. Continue Writing User Manual Section of Senior Design Documentation. |
| 28 | 11/18 – 11/24 | Complete Applicable Field Testing. Complete Writing User Manual Section of Senior Design Documentation. |
| 29 | 11/25 – 12/1 | |
| 30 | 12/2 – 12/8 | Practice Demonstrations. Practice Presentations. |
| 31 | 12/9 – 12/15 | Senior Design Project Committee Presentations |

## Financials

### Initial Projected Budget

In this section we present a preliminary project itemized budget. This budget includes projected costs for each technology we intend to integrate into our final device. It is important to note that these costs are preliminary and will not necessarily be accurate until we finish the design and fabrication of the final device. As such, we have overestimated the technology and power requirements, and projected cost for some of the items in this budget, such as in the solar section. We have chosen to overestimate these costs so that when fallbacks occur we will stay under budget, so as not surprise our sponsor.

In order to meet the requirement specification of a reproducible unit cost of less than $70 USD, for 5,000 units - the number of commercial beehives - we need to pay attention to the individual unit costs and unit cost breakpoints associated with suppliers that we choose to use.

| Type | Item/Description | Supplier | Part No. | Unit(s) | Projected EPU ($) * | Projected Exp. ($) * |
|---|---|---|---|---|---|---|
| Power | Solar Cells (6.2 W) | Adafruit | 1525 | 3 | 75.00 | 225.00 |
| | High Efficiency Synchronous Switch Mode Charger | TI | BQ24650 | 3 | 20.00 | 60.00 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | $LiFePO_4$ Batteries (1000 mAh) | Westinghouse | N/A | 3 | 25.00 | 75.00 |
| | Solar Panel Mount | Renology | N/A | 2 | 15.00 | 30.00 |
| | | | | | ** Miscellaneous Solar Costs | 150.00 |
| Hardware Prototyping | Microcontroller including RF Comms Chip | TI | MCU: MSP-EXP430G2<br><br>Comm Chip: CC1300x RF | 2 | 120.00 | 240.00 |
| | Sensors Kit for MSP430 MCUs | TI | Multiple | 2 | 35.00 | 70.00 |
| | Single-Strand 22 Ga. Copper Wire for ICs | N/A | N/A | 100 feet | 0.55 | 55.00 |
| | Varied Basic Electronic Components Kit (Rs, Caps, MOS, Diodes, Op Amps, etc.) | N/A | N/A | 4 | 15.00 | 60.00 |
| | | | | | **Miscellaneous Hardware Prototyping Costs | 200.00 |
| Hardware Fabrication | PCB Fabrication Stage 1 | Altium | N/A | 2 | 30.00 | 60.00 |
| | PCB Fabrication Stage 2 | Altium | N/A | 2 | 30.00 | 60.00 |
| | RF Comm. Chips | TI | CC1352R | 4 | 25.00 | 100.00 |
| | MCU Chips | TI | MSP432 | 4 | 12.00 | 48.00 |
| | | | | | **Sensors Costs & Miscellaneous Hardware Fabrication Costs | 200.00 |
| Software Setup | Amazon AWS Server | N/A | N/A | 1 | 0.00 | 0.00 |
| | IBM Watson AI Usage | N/A | N/A | 1 | 0.00 | 0.00 |
| | Application (Dashboard) Development | N/A | N/A | 1 | 0.00 | 0.00 |
| | | | | | ** Software Hosting & Miscellaneous Development Costs | 375.00 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Miscellaneous** | Final PCB Packaging | N/A | N/A | 2 | 20.00 | 40.00 |
| | Weatherproofing Enclosure | N/A | N/A | 2 | 30.00 | 60.00 |

**Total Projected Cost 2158.00**

** Projected Costs: These are not the final costs, just the best estimate we can provide with the information we have at this time. As such, actual costs in these categories may vary.*
*** Miscellaneous Costs: we are using this to account for unforeseen costs associated with incorporating these technologies. We have not fully estimated the power requirements and other items for our project, either, because it is not fully designed and fabricated yet.*

Our project is being sponsored in full by **Steven Eisele**, the acting President of **Pollination US Inc.**, a State-of-Florida registered commercial company. This sponsorship is contingent upon us fabricating a finished device to the marketing specifications listed in the third table of the Requirements Specifications section above. In other words, he would like us to frame our generalized Internet-of-Things Tracking/Communications System for his commercial beehive tracking needs.

**This Initial Projected Budget has been approved** by our sponsor, and he has agreed to spend **$2,158.00 USD** on realizing an end-product which can be produced to suit his needs. If any additional expense is required, this will be amended and approved below by our sponsor again before proceeding, to keep an openness and integrity between our team and the customer.

### Running Tabulations (Receipts)

This section is used to keep a continuous track of where our budget is going and when. This is accomplished using Microsoft Excel and automatically updated whenever an additional item is added, or an item is amended or changed.

[TODO: OneDrive Microsoft Excel Doc Creation + Import]

### Manufacturing Quotes (@ 5,000 Units)

Upon project completion, as per our agreement to approve the Initial Projected Budget, we will get three or more quotes for manufacturing our end-product for 5,000 individual beehives. The price-per-unit should not exceed $70 USD. These manufacturing quotes will be included below.

Bill of Materials (BOM)

## Conclusion

[TODO: Brief description of section]

[page count ends here.]

# Appendix

[TODO: Brief description of section]

## A1. References


[1] "How much does agriculture depend on pollinators? Lessons from long-term trends in crop production.," [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2701761/.

[2] "Why We Need Bees: Nature's Tiny Workers Put Food On The Table," [Online]. Available: https://www.nrdc.org/sites/default/files/bees.pdf.

[3] "Beekeeping By The Numbers," [Online]. Available: https://americanbeejournal.com/beekeeping-by-the-numbers-2/.

[4] "Honey Bee Disorders: Honey Bee Parasites," [Online]. Available: http://www.caes.uga.edu/departments/entomology/research/honey-bee-program/bees-beekeeping-pollination/honey-bee-disorders/honey-bee-disorders-honey-bee-parasites.htmlH.

[5] "Honey Bee Parasites, Hive Pests, & Bee Diseases," [Online]. Available: https://www.uaex.edu/farm-ranch/special-programs/beekeeping/hive-pests-diseases.aspx.

[6] "Comparative Analysis of Profitability of Honey Production Using Traditional and Box Hives," [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5478371/.

[7] "Temperature and Thermoregulation in the Beehive," [Online]. Available: https://www.arnia.co.uk/temperature-and-thermoregulation-in-the-beehive/.

[8] "Hive Humidity," [Online]. Available: http://www.arnia.co.uk/hive-humidity/.

[9] "Honeybee Colony Vibrational Measurements to Highlight the Brood Cycle," [Online]. Available: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0141926.

[10] "Sound Communication in Honeybees," [Online]. Available: https://beesource.com/point-of-view/adrian-wenner/sound-communication-in-honeybees/.

[11] "Bee Learning and Communication," [Online]. Available: https://en.wikipedia.org/wiki/Bee_learning_and_communication .

[12] "Honey Varietals," [Online]. Available: https://www.honey.com/about-honey/honey-varietals .

[13] "Internet of Things Market to Reach 1.7 Trillion by 2010," [Online]. Available: https://blogs.wsj.com/cio/2015/06/02/internet-of-things-market-to-reach-1-7-trillion-by-2020-idc/ .

[14] "Wireless Devices and Health Concerns," [Online]. Available: https://www.fcc.gov/consumers/guides/wireless-devices-and-health-concerns.

[15] "Pollination: Managing Bees for Pollination," [Online]. Available: http://www.caes.uga.edu/departments/entomology/research/honey-bee-program/bees-beekeeping-pollination/pollination/pollination-managing-bees-for-pollination.html.

[16] "Honeybees Behaviour," [Online]. Available: https://www.jscimedcentral.com/Behavior/Articles/behavior-2-1010.pdf .

[17] "Battery Types for Solar Electric Systems," [Online]. Available: https://www.solar-electric.com/learning-center/batteries-and-charging/battery-types-for-solar-electric-systems.html .

[18] "A Survey on Security and Privacy Issues," [Online]. Available: https://ieeexplore.ieee.org/document/7902207/ .

[19] "Beekeepers are Stealing Each Others Hives to Survive the Cutthroat Industry," [Online]. Available: https://qz.com/1275258/beekeepers-are-stealing-each-others-hives-to-survive-the-cutthroat-industry/ .

[20] "NEMA Enclosure Standards," [Online]. Available: https://www.nema.org/Products/Documents/nema-enclosure-types.pdf .

## A2. Copyright Requests

## A3. Beekeeping Terminology

A **Beehive** (or **Colony**) is collection of bees making residence, around the location of the queen bee's choosing. A colony generally contains a single queen bee (a fertile female), a few thousand drone bees (fertile males) and tens of thousands of worker bees (sterile females). The **Queen Bee** is the "leader" of the hive. The **Drone Bees** – while they do not have stingers – guard the hive and mate with the queen bee. The **Worker Bees** clean the hive, feed the larvae, and retrieve pollen.

A collection of beehives in a single area is called an **Apiary** (or **Yard**). An **Apiarist** (or **Beekeeper**) is someone who looks after the beehives in an Apiary.

A **bee brood** (or **hive brood**, or **brood nest**) is a state of the hive when a new queen bee, new worker bee, or drone bee eggs are being laid by the current queen bee and are in various stages of development up to and including the larvae stage.

**Swarming** occurs when a new colony is formed away from the original. The queen bee signals and leaves with a large group of worker bees, taking them with her in starting her new colony.

In honeybees, **trophallaxis** is the exchange of food or honeybee pheromones to communicate information about the resources available, bees and beehive.

**Honey Varietals** describe the assorted flavors of honey honeybees produce based upon the climate (temperature and rainfall), and flowers blooming which the honeybees had visited.

## A4. Relevant Code Snippets