Wireless Sensor Mesh Network for Irrigation Systems

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Table of Contents

List of Tables:

List of Figures:

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Abstract:

Pepper Oak Farms, a company that grows their own olives for olive oil and has approximately 40,000 olive trees, is in need of an efficient way to monitor the soil and atmospheric conditions that are critical to the cultivation of their trees. The company at the moment only has two sensors and has to manually place the sensors at different locations to collect data on soil moisture and temperature. This is expensive, time consuming, and a lot of effort on the owner's part to go out on the fields to collect this data. As a solution, the company would like to create a wireless mesh network with different nodes throughout the land to monitor and collect data from the sensors.

The project goals are to implement this wireless mesh network with enough nodes in the network to cover most of the area on the land and for the project to be self-monitored. To help cover costs, we will be using modules that use Zigbee IEEE 802.15.4 wireless protocols and standards which are used for low power consumption and have a range of up to 100 meters. The modules will be interfaced with Texas Instrument's Tiva C microcontrollers that will collect the output of the sensors to be later transmitted to the home network.

Chapter 1: Introduction

The goal of this project is to design a cost effective wireless mesh network for a customer, so that the customer can analyze the data being collected from the sensors at each node without having to visit each node. The design of this project would be built so it can easily be replicated by the user. The customer has sought out help from Ranch Systems, a company that specializes in manufacturing and setting up wireless mesh networks to monitor environmental data using sensors, but the cost to set up and design a complete network would be too expensive for the company to afford. As a solution, the company has seeked the Cal Poly Electrical Engineering Department and Professor David Retz to help prototype a more cost effective way to implement a wireless mesh network to monitor their crops.

A wireless mesh network follows the network topology in which there are different nodes that are connected to at least two other nodes to distribute data[1]. The gateway controls how the mesh network nodes communicate between each other and how data is routed back to the home server, where the data is collected. There are many ways to implement a wireless mesh network and we would need to implement our design to the customer's needs that will be mentioned later. The overall function of the system is shown in Figure 01.

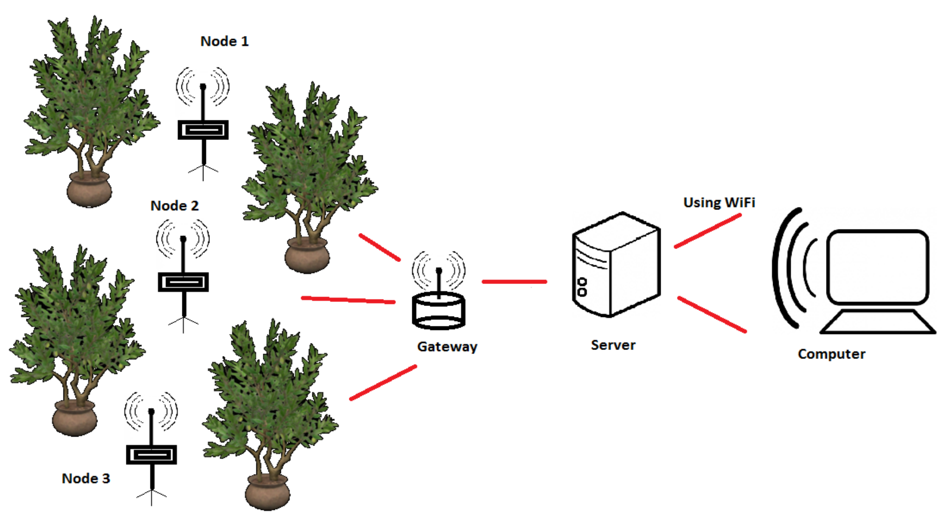

Figure 01 : Overall function of the wireless mesh network

Chapter 2: Market Research

Overview

In the agricultural business, the use of state of the art systems allows for the possibility to produce the best products. Beginning from old ways of maintaining crop health, many farmers and planters have the need of using computerized systems that measure crop wellness that provide critical information. We have grown from a very basic agricultural society back to the early humans to a society that mass produces agricultural products for billions of people. Most of all the products have a direct or indirect relationship with the agricultural business because of the fact that it governs our lives. Particularly, in the case of this product, a system of devices is needed to specifically determine soil temperature and moisture level that will allow the owner to get a better reading of what must be done and to ensure preventive measures in the case of an emergency. Through this market research, we would like to explore the different facets of wireless monitoring for agricultural uses in order to determine where our product excels amongst the other current wireless systems.

Currently, there are many companies that currently have their own effective way of wireless monitoring that allows ranch owners and farmers to know the every detail that entails growing well nurtured plants. The list of companies are seen in the following Table 01 below with their strengths and weaknesses listed after in Table 02. These companies are efficiently receiving data from points on a farm that, like our product, will collect information that is necessary for plant production. Seeing how these companies are thriving within this industry, it can be safe to say that agriculture will not be declining in the near future. Due to this, the demand for systems that can digitally store and send data to the owner is crucial for success.

Table 01: Companies who presently have wireless monitoring systems

[7]	"Mesh Telemetry Systems These consist of a central Base Station (RM210) maintaining constant contact to the central online server and software via a cellular or WiFi link, and up to 25 mesh telemetry "nodes" (RS300) spread out in the surrounding fields (although typically less than 25)." [7]
[2]	"These durable systems provide irrigators with a total system solution from a single trusted irrigation industry specialist. Our systems are designed to operate in even the most remote areas. Whether the need is to monitor flow, soil moisture, weather, water quality, ET, or other critical inputs,we are sure to have a system to meet your needs." [8]
	"HOBOnode wireless sensors monitor temperature and soil moisture conditions and transmit the data back to your computer. They enable you to view current conditions through a remote sensor, receive alarm notifications, and log data on your PC without having to run cables through the field." [9]
	"The ClimateMinder wireless network is a collection of nodes, each of which is able to communicate with the other nodes using a radio module. One or more sensors or control relays are connected to each node. Each node controls whatever sensors or relays are attached to it, communicating sensor or control data to and from the Gateway mode. The Gateway node is the node that communicates with the ClimateMinder Server using a GSM modem." [10]

Table 02: Comparing strength and weaknesses of currently providing companies

Company	Strength	Weakness
Ranch Systems	● 2.4GHz (802.15.4), 915 MHz (250mw or 1W), 868MHz (Europe) ● Typical range- 0.5 to 2 miles ● Typical run time without sunlight- 1 week ● Has Solar and Conventional Battery ● Programmable 60 secs to 18 hours ● 4 MB Memory	● Does not have probe 4 ft into ground ● Cost- about $1,000 per unit ● Output power is 5 Watts
McCrometer	● Monitor flow, soil moisture, weather, water quality, ETo or other critical input ● Mainly made for Irrigation purposes ● Can access data Smart Phone, Tablet, Personal Computer, Email, Text or Voice Mail	● Does not have probe 4 ft into ground ● More sensors than what is needed
Onset	● Logs and wirelessly transmits real-time data within a self-healing mesh network ● Notifies you of alarm conditions via email or text messages ● Onboard buffer memory helps prevent data loss ● Wide range of external sensors available ● Powerful software for organizing and viewing data	● AC powered with battery backup ● Does not have 4 ft. probe as needed per the customer ● Whole unit is $989 ● Each individual node runs at about $300
RainBird	● Integrates sensors and irrigation together	● Powered by D-cell alkaline batteries

	• 200 sensors, 20 ISDL-2400 data loggers, 40 ISR-2400 repeaters per ISG-2400 gateway. • 2.4 GHz ISM DSSS (Digital Sequencing Spread Spectrum) unlicensed frequency • Power output 10mW and 63mW per country of use regulations • Protocol: DigiMesh™ proprietary mesh network • Communication Range: Unobstructed line of sight 800 yards	• Main Customer are owners of Golf Courses • Does not include 4ft. probe.

In terms of our own product, the main factor that gives us an edge over our competitors is price. In the current market, all of the products that are being sold are controlled by the big companies. The price requirements of these products therefore are basically set by the need and the companies who control this aspect. Since there is not a huge market dedicated to wireless mesh networks, the products all run at about $300 a node and usually $1,000 for the whole unit. In addition, since within the past few years, California has been experiencing a drought that has hit many of these farmers hard. The lack of water requires that many be smart with their own resources. With this in mind, technology would lead us through the market because the need is especially needed now. Farmers are willing to pay more on the expensive side in order to reap the benefits of a good harvest.

Many of the following companies, have manufactured and mass produced these devices that in part, make a certain amount of money that allow for profit. What our product thrives in, is in the fact that everything is kept at a low price that has the same effectiveness. Our team is looking into using Zigbee protocols in order to have a wireless mesh network that is fully functional. In addition, using the Tiva C Launchpad, which are relatively cheap by today’s standards, will effectively be another factor that keeps the price low. Furthermore, other than Ranch Systems, there is not really a fully integrated mesh network that only focuses on the particular request of the client. That is, a fully wireless network that gets readings of temperature and soil moisture at different depths that is then relayed to a main server that receives this data.

Entering the market, would be initially difficult to do because the main leader of these agricultural devices that monitor crucial data is mainly led by Ranch Systems. Since they are mainly leading the market and are located here in California, they have invested their time and effort into the breadbasket of California. Since they have mass produced many of their products that have efficiently been working in many ranches, it would initially be difficult competing against them. However, after passing through the threshold of establishing our business, the potential to achieve success is imminent because of the low cost of our devices. In order to have success, potential partnerships would be crucial to make sure that our product has longevity as well as initial success. The main partners would include Texas Instruments and Zigbee since we would use similar protocols that they have already established. Texas Instruments provides for the TIVA C Launchpad microcontroller that will be used to interface the sensors and Zigbee devices. Zigbee allows us to establish a wireless network that essentially “talks” to other devices and server. Having a partnership with a company that specifically deals with sensors in agricultural based environments would be ideal but the two main partnerships would be the most ideal. From the “A Wireless Sensor Network Solution for Precision Agriculture Based on ZigBee Technology” research article, Table 03 seen below shows the clear candidate that is perfectly suited for this exact situation [3].

Table 03: Comparison between wireless LAN, bluetooth, and Zigbee [3]

Feature	Wi-Fi (IEEE 802.11 b)	Bluetooth(IEEE 802.15.1)	ZigBee (IEEE 802.15.4)
Radio	DSSS[1]	FHSS[2]	DSSS
Data rate	11 Mbps	1 Mbps	250 kbps
Slave enumeration latency	32	7	64,000
Node per master	Up to 3 s	Up to 10 s	30 ms
Data type	Video, audio, graphics,pictures,files	audio, graphics, pictures, files	Small data packet
Range (m)	100	10	70
Extend ability	Roaming possible	No	Yes
Battery life	Hours	1week	>1year
Bill of material ($)	9	6	3
Complexity	complex	Very complex	simple

1. direct sequence spread spectrum; 2. frequency hopping spread spectrum.

To enter the market key customers are absolutely crucial to show the product’s functionality and capabilities off. For our product, that can only sense temperature and soil moisture, we would need a customer that is looking for a those specific functions in a product. Ranch Systems has been able to integrate UV radiation sensors and cameras with their product. Since our product does not have all those extra capabilities, we need to find customers looking for the set specifics our product can meet for a low price. This might mostly entail of ranches and farms that have not been fully integrated with sensors but are at the beginning stages. This would be similar to our lead customer in Pepper Oak Farms, which as stated only has two sensors in their olive farm. Pepper Oak Farms would be a foot in the door as it will be a real life example of what our product is truly capable of.

Chapter 3: Requirements and Specifications

Overview of the Needs to be Addressed

In order for our design to match the customer needs, we would need to consider many factors regarding collecting and monitoring for accurate data, starting with selecting sensors that can accurately measure and output data. The customer would like to monitor the moisture and temperature of the soil. The company specified that they already use multi-level probes that are 48” long with multiple sensors to monitor the moisture and temperature in the soil every eight inches. Since the plan is to have a probe at each node, each sensor in the probe needs to be appropriately calibrated and be able to match the measured data from other sensors in the probe and also other sensors from other probes. This is important because we will later need to create and program an algorithm to properly convert the output of the sensors to a measured unit for human understanding.

The output of the sensor would need to be interfaced with a hardware platform with an appropriate hardware design that will give an output to a microcontroller. The challenge would be to create a circuit board that is small and protected because it will be located in outdoor environments. An appropriate weatherproof housing that is hermetically sealed to protect the circuit and microcontroller will need to be selected to avoid any damage to the electronic components being used.

Selection of a microcontroller will also be another important task. There are various requirements to consider when selecting a microcontroller. To fulfill the customer needs, we would need to select a microcontroller that has a 12-16 bit A/D converter to be able to read more accurate values, consume less power, have at least 2 serial ports (one for Zigbee module and one for debugging the system), have an affordable cost, and be durable. There are two candidates we have in mind that will fulfill these needs: the Arduino Leonardo and the Tiva C Launchpad TM4C1294.

Zigbee modules follow the 802.15.4 network protocols and standards are designed specifically for creating wireless mesh networks. There are many companies that build these modules that operate at different frequency bands and have different channels. To help satisfy the customer needs and keep costs low, it would be best to find a module with that has an antenna that can propagate a signal over 100 meters, has a date rate greater than 100kb/s, antenna diversity, greater than 100 dBm link budget, and low power consumption.

With the idea of having multiple nodes distributed amongst 200 acres of land, power will be an important task to consider when selecting all the items mentioned above. Most of the items will be powered by lithium ion batteries to mitigate the issue of the batteries dying out, prolonging the function for at least a year. The components that will be used have low power modes and Zigbee modules usually have a low duty cycle, so theoretically the designed system can run for up to 2-3 years, but it would be a nice commodity to know that the system won't fail due to the batteries dying out. Below are tables that address the requirements from the customer and marketing research to help support the solution to that specific customer requirement.

Table 04: Wireless Sensor Mesh Network Requirements and Specifications

Marketing Requirements	**Engineering Specifications**	**Justifications**
2. Compact for ease of use	Small and portable ● housing containing device (3in x 5in x 4in) ● Underground Pole that contain sensors (4ft w/ diameter of 3 in.)	Must be able to be moved from one location to another easily.
1. High Accuracy	Must be able to communicate with 16 A/D sensors (temperature, humidity, water depth)	In order to get more accurate data, multiple sensors for temperature, humidity and water will be deployed for one module.
7. Wireless Communication	Must be able to communicate with other modules using a mesh network protocol (Zigbee)	Wireless connectivity with similar modules in order to “talk” to each other, transferring and receiving data.
1. High Accuracy 7. Wireless Communication	Wireless range of module must be within 20 m (approximately 65 ft)	The range for each module must be small enough to communicate with each other, but still have maximum coverage
4. Withstand harsh weather environments	Weatherproof casing and hermetic sealing	Module needs to be protected from weathering and other possible external damage.
1. High Accuracy	Sensor Measurements within 5%	The data must be accurate to be accountable.
5. High Resolution 6. Power Efficiency	Time between data collection: 15 min	In order to reduce power consumption, timed data collection will be used to bring more efficiency to the

		battery.
5. Wireless Communication 6. High resolution	Design of wireless network follows IEEE 802.15.4 protocol	The protocol gives requirements for frequency band, data rates, etc. for the network to be considered valid.

Market Requirements
1. High Accuracy (within 5%) 2. Compact and simple for ease of use and replicability 3. Cost Effective (not available at this time as client has not released a working budget) 4. Withstand harsh weather environments (temperatures from 20℉ to 120℉, maximum 5” of precipitation) 5. High Resolution 6. Power Efficiency (not have to worry about changing batteries) 7. Wireless Communication

Project Roles

Due to the size of this project, several roles to meet these requirements have been formed. Below is the description of each team member’s role.

Rosana: *Wireless Antenna (802.15.4 network protocol) & Hardware Platform*

The design for the hardware include the antenna that transmits and receives data and the microcontroller that receives the data. This role involves research on the IEEE 802.15.4 network protocol for low rate wireless personal area networks. This standard defines the physical layer and media access control layer. It lays out specifications on the frequency bands to use depending on location, modulation types, data rates, etc [12]. The antenna designed must be designed to be durable, yet not in the user’s way. The design is also dependent on the frequency band used. For the microcontroller, we considered the Arduino Leonardo and the MSP430. The Arduino has more I/O pins and more data but the MSP430 has a lower unit cost. We are not considering the Raspberry Pi because it is more complex since it has it’s own operating system. This much functionality is not required for this project since we are communicating back to the user's personal computer. We eventually chose the TIVA C TM4C1294 Launchpad, another Texas Instruments product because of the documentation found on integration between the

Oswaldo: *Software Platform & Gateway*

A gateway is a bridge that connects wireless devices to the internet [6]. For this project we will be using TI's Z-Stack™ Linux Gateway, this will allows to enable remote monitoring and control the Zigbee modules at each node. The Z-Stack gives us a simple API (application programming interface) for home automation, incorporating TCP/IP to ZigBee bridge and enabling faster development of applications and easier integration of low power connectivity solutions [6]. The API will let us develop a friendly GUI so that it will be easier to access the database and hardware information. MAC, IP, and DHCP configurations can all be edited and accessed to set network parameters for the nodes in the mesh network. The Gateway will then route data back to the home server for analyzation and storage. The data from the home server will have remote access for the customer to be able to access real live data remotely..

Justin: *Power Management & Packaging*

Energy source for the 5V powered module and its overall design. A rechargeable battery hooked up to the system will be researched and implemented into the prototype's design. Since the battery will be powering the module for an extended amount of time, a battery management system will also be implemented. As for the packaging, the module for the sensors and antenna will be enclosed into a weatherproof and durable case so the microcontroller and delicate circuitry will be protected from water, dirt, shock, etc. The packaging has functionality in two ways: the one described earlier, and the other as an easy to assemble system. The implementation of the system is in two parts, where the sensors will be inserted into the ground, followed by the connection of the main component, where the microcontroller rests.

Stanley: *Sensor Technology & A/D Sensor Channels*

The whole device revolves around sensors that will pick up temperature and moisture levels at the indicated levels of interested as requested by the customer. Using the sensors, the appropriate Analog to Digital converters are needed in terms of getting the appropriate information sent to other devices as well as the gateway, which will involve sending it to the main computer. The role comprises of finding the right sensors that will withstand the environment of being under ground as well as being water proof. Finding the right sensors, for this field of application would be key in order to obtain the right data. Using the sensors, they will then be used by the 10 bit microcontroller so that the information can be relayed to the appropriate places.

Nabil: *System Management & Backend/Server*

System Management includes being able to achieve maximum productivity in terms of having the product running and working with ease. This includes having the product up and running when first installed and not facing any barriers. Other parts of the job include making sure the parts necessary for the product is available and inventoried. One of the most important aspects involving this product is making sure the server is monitoring and collecting data the way it should. Overall it will be necessary to manage and monitor the product for maximum productivity and long term use.

Managing the backend server would include being able to make all the data and information available for the customer to check on his phone through an app or something similar. This would require knowing working knowledge of phone apps and design. There is already a working application involving linux for Pepper Oak Farms with which we would integrate our design into. To complete all this, information on how servers work is also necessary.

Although each role has been specified for each person, there will be overlapping roles in case more manpower is needed. Advisors will also help out with information/progress when needed.

Chapter 4: Functional Decomposition

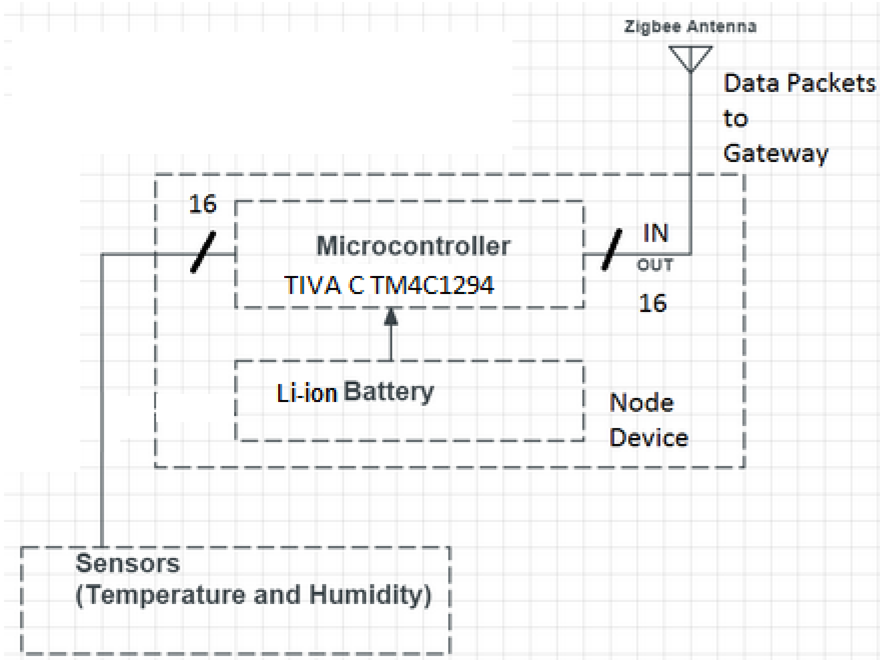

Figure 02a: High level block diagram of sensor module

The block diagram shown above depicts the inputs and outputs of the sensor module. The 10 A/D sensors collect the external data into the microcontroller and compiles data packets to be sent wirelessly using the Zigbee antenna or directly to the gateway using a data cable. The power source will be 3.7 li-ion battery cells, where the battery will not have to be changed out or recharged for at least one year. The functionality is described below.

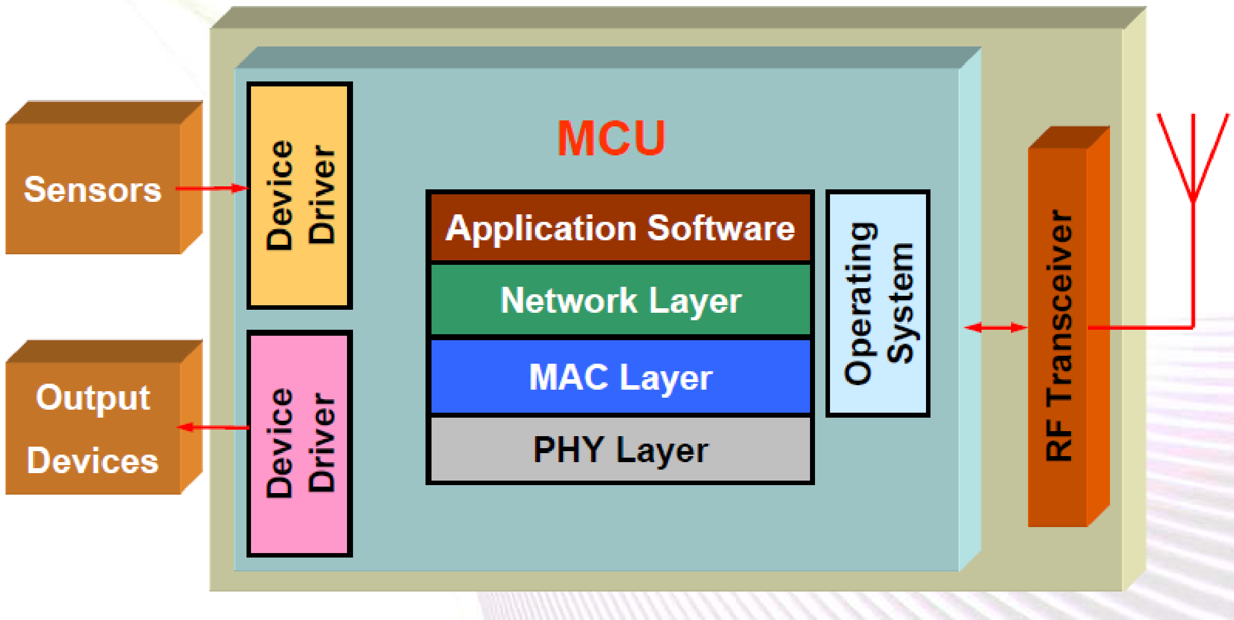

Figure 02b: High level block diagram of Software/Network Layers

The block level diagram seen on Figure 02b shows the software and network layers of the Zigbee.

"*ZigBee is a type of LR-WPAN technology and is built upon the lower layers of the IEEE 802.15.4 LR-WPAN standard. While the 802.15.4 standard defines the lower-level Physical (PHY) and Media Access Control (MAC) layers, the ZigBee standard defines the higher-level Network and Application layers as well as the security services. The top layer in the system model is where the customer application resides. In terms of general functionality, the Physical Layer provides the basic radio communication capabilities, the MAC Layer provides reliable single-hop transmission, the Network Layer provides routing and multi-hop transmission for creating more complex topologies, the Application Layer provides device and network management functions as well as message formats, and the Security Services Provider establishes the trust infrastructure of the network and provides essential security services such as cryptographic key management and admission control for nodes joining a network.*"[13] By understanding the network layer of each ZigBee module, we will be able to mount each module to the

Gateway and set up paths of how the modules should communicate with each other and route data.

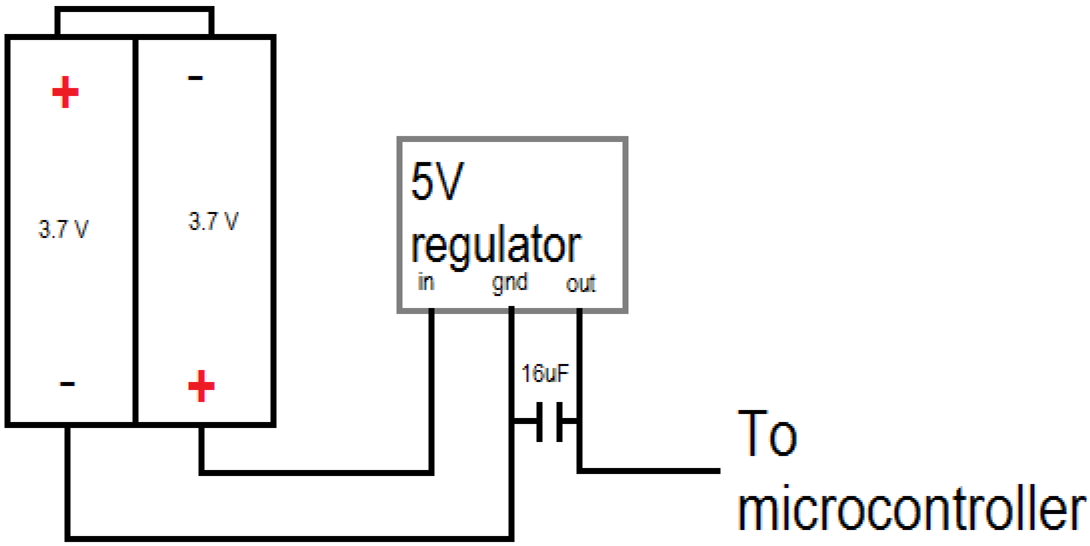

Figure 02c:Battery Power System diagram for microcontroller/sensors [14,15]

The circuit above shows the circuit diagram for the power source which connects to the module. This schematic is the final design of the power source of the microcontroller. The same battery design is used for powering the sensors, where the battery is just one 3.7 V li-ion cell and the regulator is a 3.3 V type. The reasoning for the capacitor in between the output and ground node of the regulator is to stabilize the output voltage.

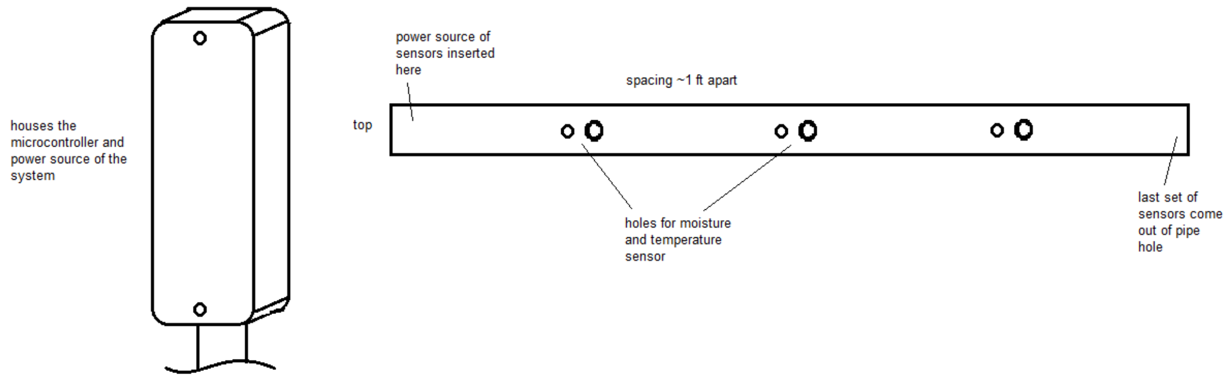

Figure 02d:Packaging of the system

This diagram shows the packaging design of the system. The microcontroller with antenna is in the weatherproof box and the ~4 ft. pipe houses the moisture and temperature sensors.

Table 05: Functionality of Sensor Module

Input/Output	Name	Description
Input	Sensors	There will be up to sixteen sensors that will connect to the sensor module. The sensors will input data concerning the soil temperature and moisture, atmospheric temperature and humidity. This data will be taken in by the microcontroller and converted from analog to digital. The data will also be processed and sent to the antenna to send back to the main node.
Input	li-ion battery (18650)	The battery will be powering the sensor module. This is also a rechargeable battery type with high mAh to last for at least 1 year without charge.
Input and Output	Zigbee Antenna	The antenna connected to the sensor module will act as an input by taking in data about the surrounding nodes. It will behave as an antenna in a mesh network. The antenna will also behave as an output by sending out data collected from the sensors.

For test and verification, we will have to ensure that the data collected by the sensors is accurate and the microcontroller is calibrated to process the voltage values that are being outputted to the sensors. To do this, the individual sensors will have to be tested and calibrated on its own. To test the soil moisture sensor, we will place the sensor in a soil sample from the Santa Ynez region (where the orchard is found) and add water incrementally while recording the voltage output from the sensors. Also, we will subject the soil sample to different temperature conditions and take similar recordings. The data recorded will be used to calibrate the microcontroller to process the data. Likewise, the procedure will be done for the atmospheric temperature and humidity sensors without placing the sensors in the soil.

Once the sensor module has been developed, we will have to test whether the nodes can communicate with each other. To test this, we will have to turn off all the nodes except two modules and ensure that they can exchange information in between each other. After this, we will have to ensure that even though all the modules are on, the modules can exchange information with any surrounding module.

Another component that will have to be tested is the power system. We will have to ensure that the li-ion battery cell can supply sufficient power to charge the battery. We will record the power considerations for the battery and measure how much power is being supplied to it. If the battery doesn't get enough power, we will have to redesign the power source to supply enough amperage, which the li-ion batteries are capable of.

After configuration and testing of the sensors, microprocessor, and zigbee network, the gateway and backend can be fully tested. The first test would be checking whether the gateway receives the correct packets of information sent between nodes on the zigbee network. From there it would be necessary to retest with the other components included to see whether the sequence of transitions between parts is seamless. Another major part in testing would be checking to see if the packets are sent to the backend server wirelessly from the gateway. It would require having a working C program to read out the data sent from the gateway on the server. Once these individual aspects are working, the overall system can be tested as a whole checking each part along the way.

System Design and Operation

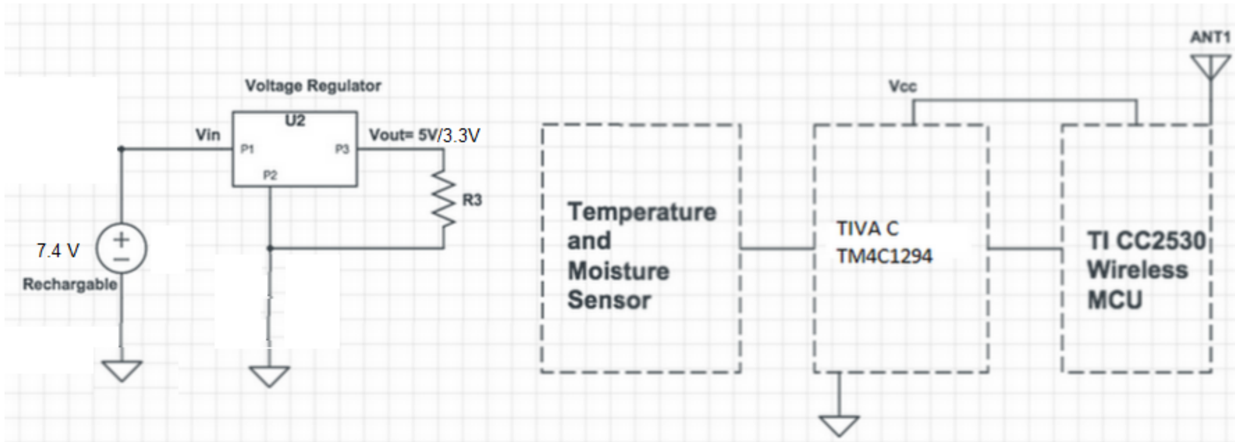

Figure 03a: Node system design with components used

Each node will be use the same components as seen on Figure 03a. The device will be powered by a 7.4V li-ion battery series connected to a LM2936 Voltage Regulator. The rechargeable battery is configured like the one seen on Figure 02c, this will give the ability for the node to be long lasting and mitigate issues of replacing batteries constantly. Vcc on figure 03a describes the whole powering unit that will power the TI Tiva C and the TI CC2530 MCU. There are many reasons why we are going with the TI Tiva C microcontroller and the TI CC2530 MCU, they both have low power consumption and are very affordable compared to other competitors. Another big factor is the compatibility between the MCU module and TIVA C microcontroller, they are both made from Texas Instruments, thus making easier to interface and pair the devices. The TIVA C will receive data from the temperature and moisture sensors and convert it to a human readable unit. The CC2530 will later receive that data and convert it to be sent as a data packet following the Zigbee 802.15.4 network protocol.

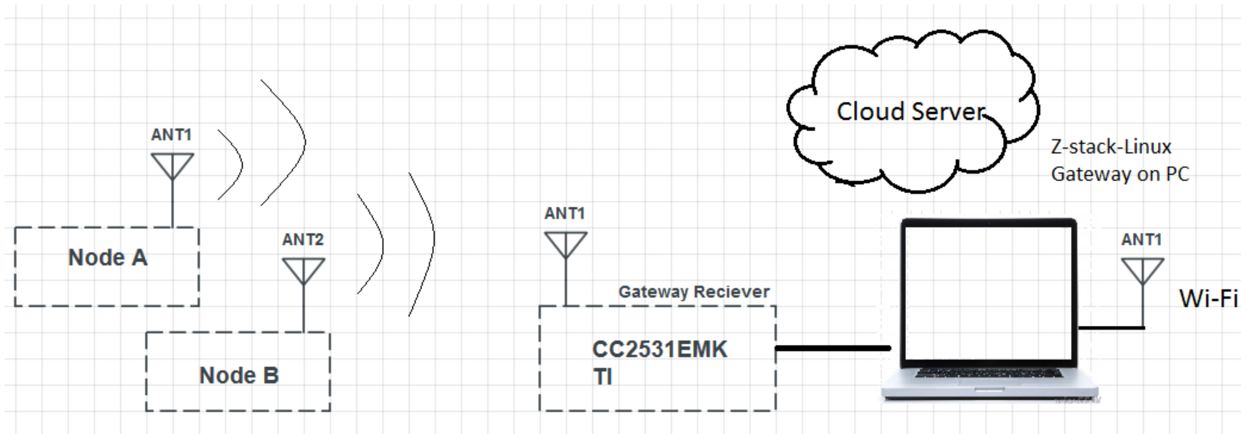

Figure 03b: Mesh Network Functionality block diagram

Figure 03b shows the functionality and operation of the wireless meshed network. A node has all the components described in figure 03a. As seen above, Node A sends a packet of data “MSG A” to its closest neighbor, Node B. If there is a node in between Node B and the gateway receiver, Node B will route MSG A to that node, in this case there is not. Node B is configured by the Gateway receiver to send any data packets to the gateway, the gateway will then reformat MSG A from the ZigBee network protocol to the WiFi network protocol. The TI CC2531EMK is another wireless dongle and it will be configured as the gateway receiver. The TI CC2531EMK will be connected to a Linux based computer and will be running the Z-Stack-Linux Gateway. Again the selection for the TI CC2531EMK is due its cost and its compatibility with the other TI devices. Another big reason is also that when you buy the gateway dongle, it comes with the Z-Stack-Linux Gateway software use to develop the mesh network and mount devices to the network. This software will make monitoring and configuring the network a lot easier, this software is also free. After receiving the data at the gateway, we can later send the data to a cloud server so the customer can access the data remotely. The data being saved on the servers, will be mostly strings of data and will not require much space. 1 TB of space on the cloud server should be more than enough to be able to store data for many years.

Soil Metrics

One of the most crucial parts of this project was the ability to measure both soil moisture levels as wells as temperature at the different depths. The probe being 4 feet has temperature and moisture sensors at every 12 inches allowing for measurements at different levels. These measurements are important to the farmer because of the fact that they provide vital information regarding plant health and well-being.

Soil Temperature Sensor

In the main industrial size nodes, sensors are the source for the huge cost for wireless mesh networks. Since we were using a very simple microcontroller, we chose to use basic circuit components to get functionality. We used 9k NTC thermistors, that could be easily implemented with the ADC values of the microcontroller board. With our board, we were able to have 10 bits of resolution giving us a range of values that would indicate the precise measurements.

Since the thermistors did not come calibrated, the calibration measurements were done manually in order to achieve high level results. The thermistors leads were not long enough so wires were soldered on in order to extend through the four foot pole all the way to the ADC. After the wires were attached, epoxy was added to the thermistors in order to ensure a solid sealing from the leads and the sensors itself. Water corrosion could eventually wear down the thermistors, which affects its functionality. To fight the adverse effects, epoxy was used to cover the whole sensor except for the tip which is where the thermistor is.

The circuit itself was set up in a basic voltage divider circuit that monitors that changing voltage over the thermistors. As seen in Figure 4b, the voltage varies as the thermistors changes to the surroundings. Instead of obtaining the voltage, we directly take the ADC reading from this point in order to keep all the reading consistent. The resistor in series with the thermistors had to be a significantly sized resistor in order to resist the effects of self-heating. During self-heating, the current flowing through the circuit slowly but gradually heats up the thermistor causing the whole data series to be skewed. We solved this problem, by applying a 10k resistors which limits the current to less than 1 mA.

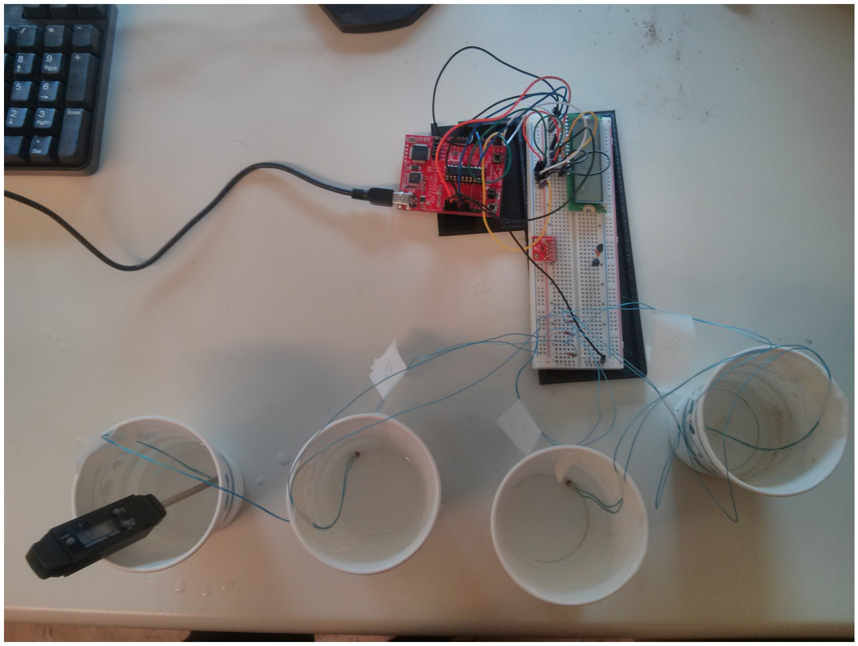

Figure 4a: Soil Moisture setup with the MSP430 microcontroller

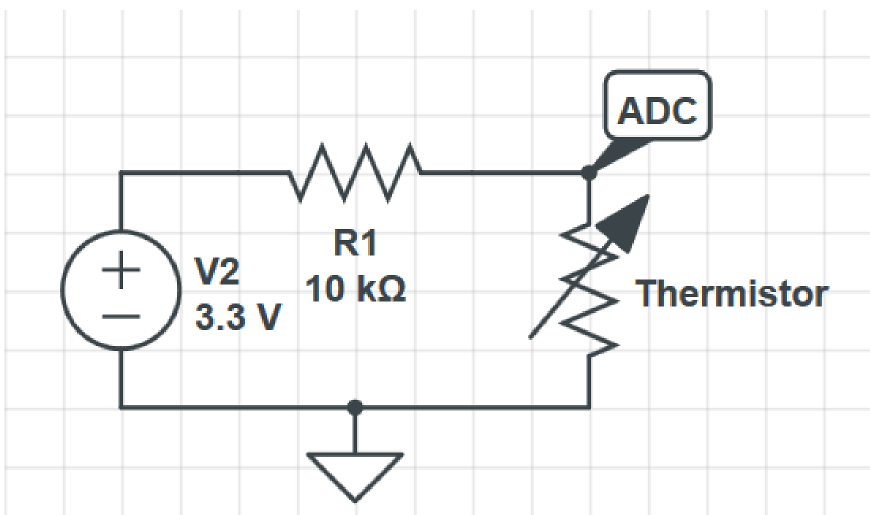

Figure 4b: Soil Moisture Circuit Schematic

Then after the thermistors were prepared for calibration, the thermistors were placed in a bath that would a temperature range seen in figure 4a. Initially, there would be a cup of warm water usually around 110 degrees Celsius, and slowly ice cubes were placed until the temperature was eventually 10 degrees celsius. Realistically, the soil temperature under the ground is usually lower than what it is in the air. For this reason, the thermistors were calibrated with more sample points in the colder regions to ensure the correct level of accuracy.

After the data points were collected, using Excel were were able to see the trend of the data points. Ideally, the data points should have a trendline that uses higher order approximation such as Least Squared or Steinhardt but for our purposes to get basic functionality, we used the trendline feature in Excel to get the closest equation possible. Unfortunately, the whole system was not integrated together so the equation was not used but was capable of reading the ADC to give the current temperature.

Soil Moisture Sensors

Similar to the soil temperature sensors, the customer wanted to know the amount of moisture within every 12 inches of the soil. With the drought going on, the efficiency of the roots absorbing water is key to prevent over usage.

The sensor we used in order to determine was the ITEAD Electronic Brick Moisture Sensor. These sensors were resistive based so essentially they determine the resistance between the two metal prongs that associates with a certain moisture level. This sensor was unique because an analog or digital output could be read. The digital output would just indicate if the soil was wet or not while the analog would give a particular reading based on the amount of water. A total of 12 sensors were used in order to calculate the reading.

In terms of calibration, after a series of trials, the calibration seemed to be very tedious because the analog reading seemed to vary tremendously and was not consistent. The problem that came out was the fact that the temperature affected the resistance of the soil giving different readings every time. Due to this, we settled with just indicated whether or not the soil was wet.

Zigbee Test and Development with Tiva C

Figure 5a: Zigbee coordinator sending data to router

Testing RF Zigbee Modules

Since we were using TI MCU, we would need to find an adequate Zigbee RF module that would work with the TI MCU of our choice. We decided to buy the CC2530 Development kit that included two CC2530 Zigbee modules, a CC2531 USB dongle to act as our gateway, and two SmartRF05EB evaluation boards used to test and program the CC2530 devices. The kit also came with instructions on how to perform, program, and run the test. Figure 5a shows a test were one of the CC2530 devices was programmed as a coordinator and sends a text message ("Hello Seedlings") to the other Zigbee device used as a router to receive the message and route back to the end point.

The two devices are synced up to the same network manually, and the coordinator would send the packet of data every 5 seconds. Different test were also conducted to measure RF parameters like the received signal strength indication (RSSI), Signal-to-Noise Ratio (SNR), and also the Packet Error Rate (PER) test used to measure the ratio between the packets that are lost and total packets being sent.

Selection of Microcontroller:

To be able to send the ADC data from the sensors wirelessly to the main Gateway and Server, we would need to interface the sensors with an appropriate Microcontroller (MCU) and a compatible Zigbee Module. Our original plan was to use the Texas Instrument MSP430G2 Launchpad MCU because there was an adapter (TI EM Adapter BoosterPack) to interface the MCU with the Texas Instrument CC (TI CC2530 in our case) wireless module. While it was physically capable of interfacing the MSP430 and the CC2530 with the EM Adapter Boosterpack, we later found out that currently there is no software support or libraries to interface the MSP430G2 Launchpad and the CC2530 Zigbee Module. After already investing in the devices and TI products, we contacted TI engineers through the TI E2E message boards to find out what product we can use for our project. A TI engineer recommended that we follow a manual of a previous project that is similar to ours using the TIVA C TM4C1294 Launchpad. After examining the manual, we were sold that it would be our best option to move to the TIVA C Launchpad. Since there was software to support the interface between the MCU and Zigbee Module, we would also continue to use the EM adapter to interface the two. While moving to the TIVA C launchpad would allow us to continue to use the TI products already purchased, one of the goals of our project was to have a low power MCU and the TIVA C Launchpad with its faster processor and complexity consumes more power than the MSP430.

Software Testing and Development

Once the TIVA C launchpad was acquired, we finally had all the components to build a functional wireless mesh network. The software framework that TI provided, allows us to customize the software to fit our needs. The TIVA C uses a real time operating system (RTOS) which uses existing proven software components to ensure reliability and quality. Additional application extensions where needed to use the RTOS on CCS v6. A terminal emulator like Putty was also needed to interface the serial port of the TIVA C and the PC to run the software test using the command line prompt . The test that was to be ran was the data send and receive test, were we would have two Zigbee devices being able to send and receive text messages back and forth.

There was issues we ran into, that were not resolved by the time of the Senior Project expo. When running the data send and receive test, we were not able to join a network after being prompted if we would like to join a network. A reason for this problem is due to the CC2530 Zigbee Network Processor (ZNP) was not configured to use Universal asynchronous receiver/transmitter (UART). Modifying the code for the CC2530 ZNP was needed to enable the device for UART. Changes were done and the same issue was not done. This is how far we were able to get. The issue is still in progress and needs to be resolved.

Software Development with the Tiva C Launchpad

Switching from the MSP430 to the TIVA C Launchpad proved to be a challenge. First of all, the Code Composer Studio that we used to program the microcontrollers had to be modified to accommodate the Tiva C. When the drivers located on Texas Instruments' website were not installing correctly, the Code Composer Studio software had to be uninstalled and installed again and it involved downloading the drivers for the Tiva C and the LM Flash Programmer, which was a recommended download by Texas Instruments. Once everything was configured, we prepared to use Code Composer

Studio to upload code onto the Tiva C. Most of the code came from the sample code provided by Texas Instruments and other instructables online. The software flow diagram shown below in Figure XX illustrates the program flow. The timer interrupt is programmed to execute every 7.5 seconds. Then, the variable count is used to keep track of how many times the interrupt executes. When count equals 120, a period of 15 minutes has gone by and that is when the ADC is called and the microcontroller reads the voltage levels from the sensors. Each sensor has a different algorithm that is used to convert the value into a temperature or moisture reading. If count does not equal 120, the microcontroller enters sleep mode to save power until the next interrupt is called.
In active mode, the microcontroller draws approximately 30 mA, but in sleep mode, it draws 4.5 mA so this helps with power consumption.

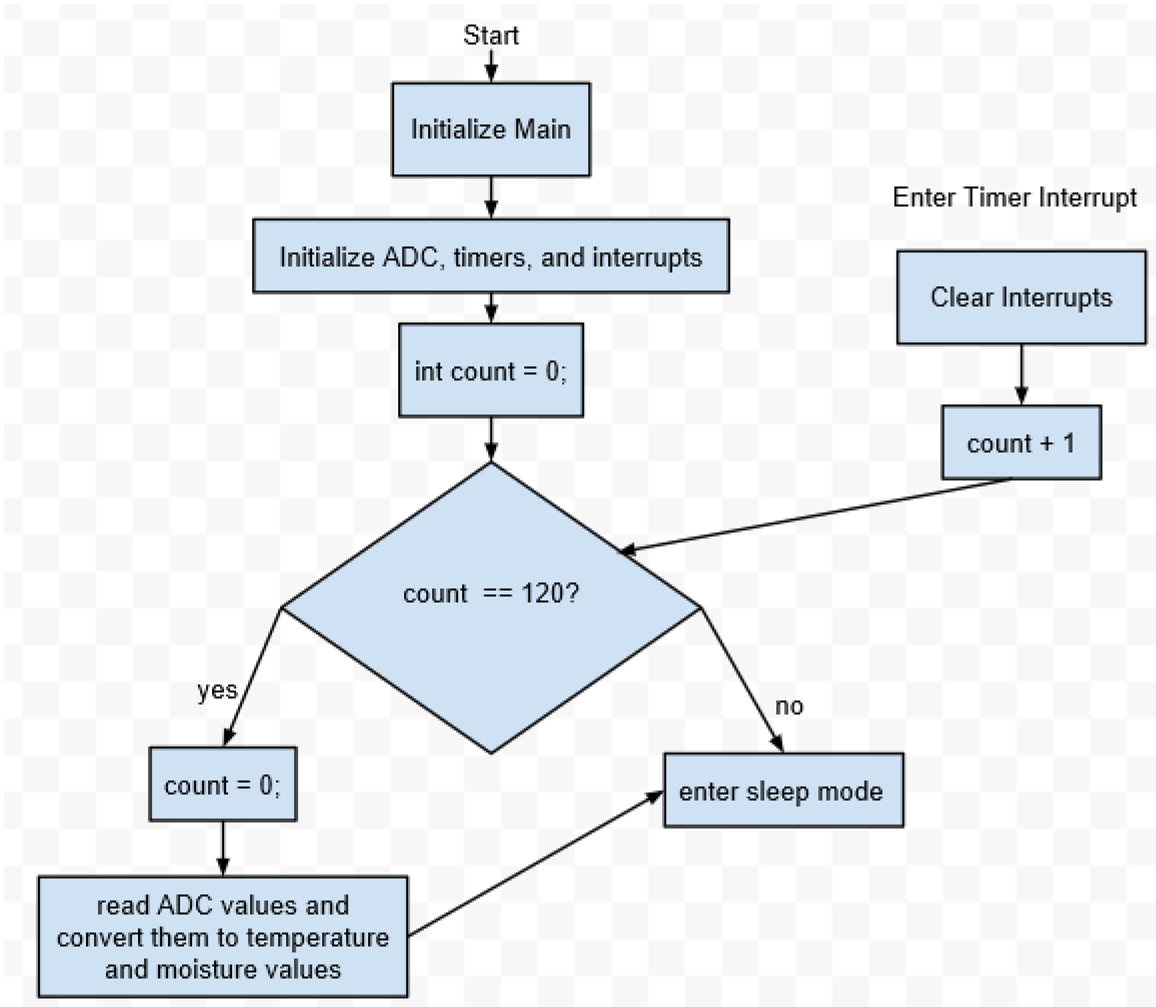

Figure 6a: Software Flow Diagram from Main to Interrupt for TIVA C

Testing Gateway and Backend Server

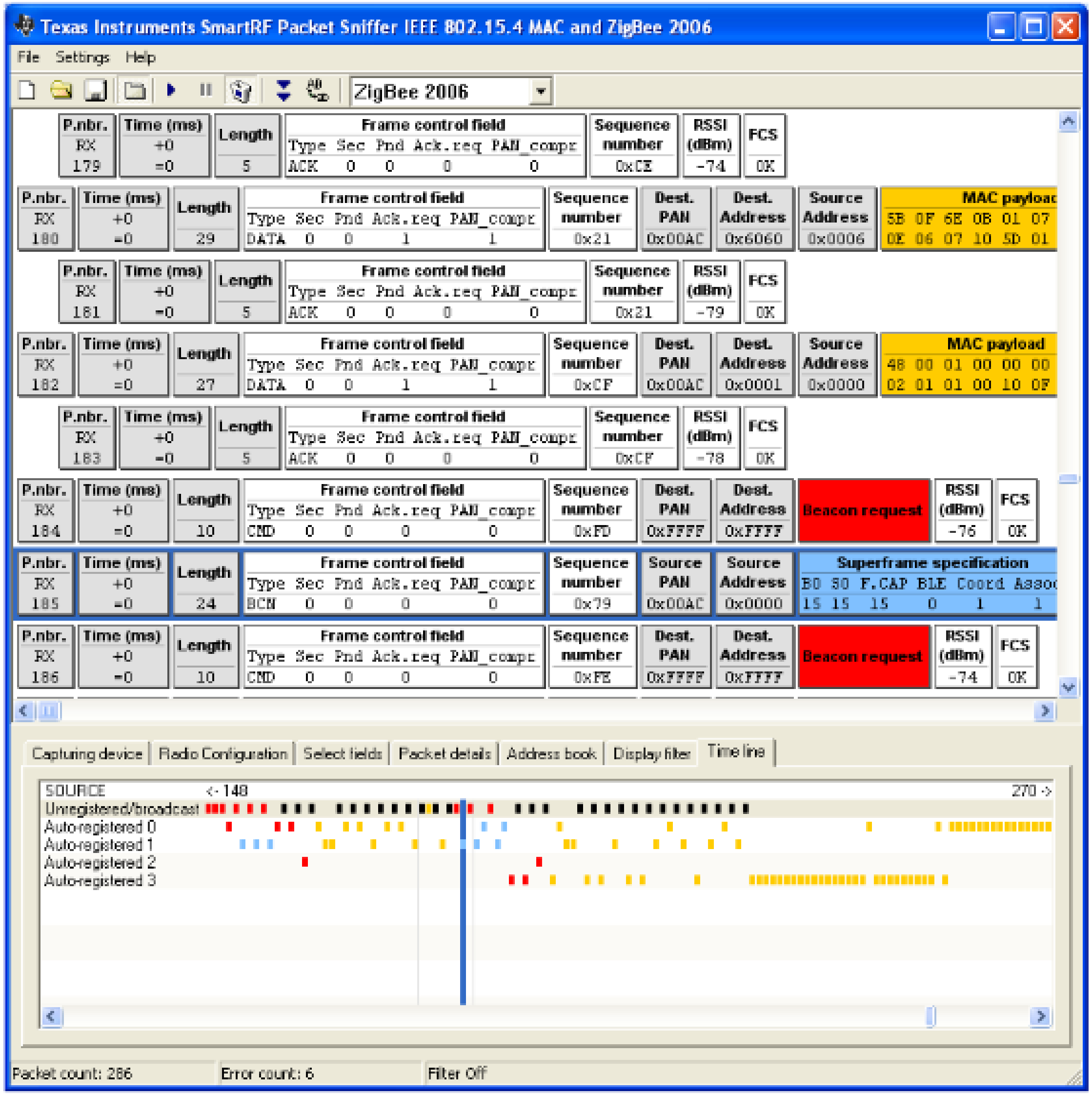

Figure 7a: SmartRF Packet Sniffer Test Setup

The CC2531 USB dongle in the development kit acted as the gateway to the Zigbee network. It was necessary to read the full manual on the gateway to understand how it worked. Other important documents included how it correlated with the CC2530's as well as the packet sniffer software manual which are all available on the TI website. The gateway would have to be plugged into a USB port to access the information received. Figure 7a shows the packet sniffer software interface with the received packets. The initial test was done with the SmartRF05EB evaluation board and CC2530 zigbee modules which was a success. After the actual boards were programmed to send “Hello Seedlings” across the nodes to be received by the gateway. The payload data at first did not make any sense since the program encrypted the data show it could not be read easily. Going into the “Hello Seedlings” program in IAR, the encryption had to be turned off before the payload data read what was expected. Once the packets are received they can be saved as a PSD file through the given software. Each step regarding the gateway had to be manually accomplished from receiving packets, to saving the data, and to displaying it. This was one of the major issues that need to be fixed.

Software and Development

Similar to the software testing and development of the Zigbee network and CC2530's, there were unresolved issues regarding the backend. Since the Zigbee network is on an IPV6 protocol it was difficult to translate the packets received and sent to the IPV4 protocol necessary to send the packets to the backend server through wifi. This required an understanding of network protocols, the functional process of servers, and the internet. Since IPV6 is new and there is no backwards compatibility with IPV4 it required a strong foundation on networks. Multiple options were researched but a possible viable solution to this issue is the use of a beagleboard. The gateway would be plugged into the USB port, an ethernet cable would need to be connected, and the board would need to be programmed to transfer the packets of information seamlessly to the server. The board would essentially act as a converter between the two networks while also getting rid of the need to handle the gateway manually. This solution still needs to be tested as a solution to the unsolved issue.

Conclusion

The environmental impact of this project could be substantial due to the recent drought. By monitoring the humidity and temperature, farmers can find out at what temperature and moisture level produce the best crops while knowing if they are over watering their crops. The product we are producing will provide farmers an affordable, accurate, and small packaged device that will be easy to maintain and monitor. The project will be continued and be reproduced, but due to poor development software and hardware from Texas Instruments, the next group of senior project students will be better off switching to Adruino. Adruino has all the software and information available and will provide a more affordable and power efficient product then using Texas Instruments and their laundry list of requirements and licensed software. Overall, knowing the impact of this project has motivated us to continue to monitor and help out the following students that will continue to work on the project.

Appendix A: References

[1] Margeret Rouse, "Mesh Network Topology (Mesh Network)" [Online] , Available: http://searchnetworking.techtarget.com/definition/mesh-network ,Oct 2014

A summary of how wireless mesh networks work. It defines the various types of mesh network configurations and nomenclature for mesh networks.

[2] Ken Masica Lawrence, *Livermore National Laboratory*, "Recommended Practices Guide for Securing Zigbee Wireless Network in Process Control System Environments", April 2007 https://ics-cert.us-cert.gov/sites/default/files/recommended_practices/Securing%20ZigBee%20Wireless%20Networks%20in%20Process%20Control%20System%20Environments.pdf

A document pertaining to the use of Zigbee wireless networking. It is a guidebook that contains information on how to set up and operate Zigbee networks as well as the system requirements and conditions.

[3] M. Keshtgari and A. Deljoo, "A Wireless Sensor Network Solution for Precision Agriculture Based on Zigbee Technology," Wireless Sensor Network, Vol. 4 No. 1, 2012, pp. 25-30. doi: 10.4236/wsn.2012.41004.

This paper explains how wireless sensor networks are useful for agricultural issues. The system described uses Zigbee protocol and monitors climate and atmospheric conditions and employs a control system based on the data collected to change these conditions.

[4] IEEE, (2013, 4 November) "IEEE Code of Ethics" [Online], Available: www.ieee.org/about/corporate/governance/p7-8.html

This webpage contains a list and a thorough description for each of the IEEE Code of Ethics. This document helps to determine what parts of our project are infringing or could potentially infringe on ethical ideas.

[5] R. Ford and C. Coulston, Design for Electrical and Computer Engineers, McGraw-Hill, 2007, p. 37

This book contains information used to perform a cost analysis. The equations used helped determine optimal costs and labor costs.

[6] ZigBee Home Automation Gateway reference design, [Online], Available: http://www.ti.com/tool/CC2531EM-IOT-HOME-GATEWAY-RD?DCMP=zbgate&HQS=ep-con-wcs-tdesign-zbgate-conw-tidesigns-20140610-en

Information regarding the gateway and how it functions. The article is necessary in understanding the creation of a connection between all the different sensor nodes and the internet. Defines the features and also has design files available to help with the design process of our product.

[7] http://gallica.ranchsystems.com/wp/wireless-network-units-3/

One of the Competitors in Wireless Mesh Networks at Ranch Systems. The main competitor that provides wireless mesh networks. Gives information regarding Ranch Systems two types of wireless network units. Information essential in creating a better product.

[8] http://www.mccrometerconnect.com/
One of the Competitors in Wireless Mesh Networks at McCrometer. Information on what the competitor has to offer.

[9] http://www.onsetcomp.com/hobonode-wireless-sensors
One of the Competitors in Wireless Mesh Networks at Onset. Information on what the competitor has to offer.

[10] http://www.rainbird.com/ag/products/ClimateMinder/
One of the Competitors in Wireless Mesh Networks at RainBird. Information on what the competitor has to offer.

[11] "2012 Master Catalog and Price List," Ranch Systems, Novato, CA, 2012, pp 21. http://www.ranchsystems.com/ssite/rs-catalog-2012.pdf
Gives the pricing lists for all of Ranch Systems' products in 2012. Page 21 gives the pricing and product page for their sensor probe that we are comparing to.

[12] J.T. Adams, "An Introduction to IEEE STD 802.15.4," Freescale Semiconductor Inc., Tempe, AZ, 2006.
http://www.sonoma.edu/users/f/farahman/sonoma/courses/cet543/resources/
This paper gives an overview of the IEEE standard 802.15.4 which lays out the specifications of low-rate wireless personal area networks. The author is considered an expert in wireless communications and his focus is in Zigbee communications.

[13] Ken Masica, "Securing ZigBee Wireless Networks in Process Control System Environments"
https://ics-cert.us-cert.gov/sites/default/files/recommended_practices/Securing%20ZigBee%20Wireless%20Networks%20in%20Process%20Control%20System%20Environments.pdf
This paper gives an overview of the IEEE standard 802.15.4 and the network protocols used to configure Zigbee. There are useful block diagrams showing the different layers in the Zigbee network protocols.

[14] http://www.ti.com/lit/ds/symlink/lm2936.pdf
This datasheet shows the specs for the voltage regulator to supply a 5 volt output. This is needed to design the battery system to power the microcontroller.

[15] http://www.ti.com/lit/ds/symlink/lm2936.pdf
This datasheet shows the specs for the voltage regulator to supply a 3.3 volt output. This is needed to design the battery system to power the sensors.

Appendix B: Senior Project Analysis

Project Title: Wireless Sensor Mesh Network for Irrigation Systems

Students:
Rosana Cheruvelil
Oswaldo Garcia
Nabil Haque
Justin Ignacio
Stanley Thomas

Advisor: David Retz and Bowen Liu

1. **Summary of Functional Requirements**

   This project is centered around the design of a wireless mesh network that complies with the IEEE 802.15.4 protocol for wireless personal area networks. There will be sensors that register data on soil moisture, soil and atmosphere temperature and the device will have antennas that communicate the data back and forth between other nodes. The data will be taken in fifteen minute increments and the communication between nodes must be accurate and reliable. The data will then be processed using analog to digital converters on microcontrollers. The software on the microcontrollers will process the data and be used to predict weather conditions or control the water consumption in certain areas.

2. **Primary Constraints**

   Our main constraint will be following the IEEE protocol for low-rate wireless personal area networks. This protocol specifies the physical and media access control layer for our wireless network, such as the frequency band or the data rate. Another difficulty is laying out the sensors in an efficient way to maximize coverage of the area but still have reliable transmission. Since wireless communication is our goal, the line of sight should ideally be clear but this is not possible since we are working on an olive tree orchard. Therefore, we will have to place the hardware in strategic locations. Other difficulties have to do with efficient designing, like low cost hardware and minimum components.

3. Economic

The Gantt charts found below in Figures 03 to 05 chronicle the development process. It is split up by quarter and the major deadline is the Senior Project Expo in May. The goal at the end is to get a fully working prototype that has been tested. Some of the high risk items, that may affect our schedule are:

- Failing to reach deadlines
- Not having appropriate research before implementing
- Parts delivery delayed / Having faulty equipment
- Not fully testing the capability of the whole product
- Interfacing the microcontroller with the appropriate sensors in a 4 ft. probe
- Getting Zigbee to function properly
- Server integration with wireless network to read out data

Task	Start Date	End Date	Duration	Fall 2014									
				Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Abstract	13-Oct	15-Oct	3										
Requirements and Specs	15-Oct	22-Oct	8										
Block Diagram	20-Oct	22-Oct	3										
Literature Search	8-Oct	23-Oct	26										
Gantt Chart	23-Oct	24-Oct	2										
Cost Estimates	24-Oct	25-Oct	2										
Advisor Feedback	21-Oct	25-Nov	35										
Final Pass Definition Document	3-Nov	24-Nov	21										
Research and Order Parts	27-Oct	24-Nov	28										
Perform Research	8-Oct	24-Nov	57										

Figure 08a: Fall 2014 Gantt Chart

Task	Start Date	End Date	Duration	Winter 2015									
				Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Order Parts	5-Jan	12-Jan	7										
Design Network	5-Jan	19-Jan	14										
Simulate and Troubleshoot Network	19-Jan	2-Feb	14										
Integrate Sensors, Antennas, and Hardware	2-Feb	16-Feb	14										
Test Individual Components	16-Feb	2-Mar	14										
Adjust and Finalize Design	2-Mar	9-Mar	7										
Develop Software	12-Jan	16-Feb	35										
Package Design	23-Feb	9-Mar	7										
Manage System	2-Mar	9-Mar	7										
Design Data Server	16-Feb	23-Feb	7										

Figure 08b: Winter 2015 Gantt Chart

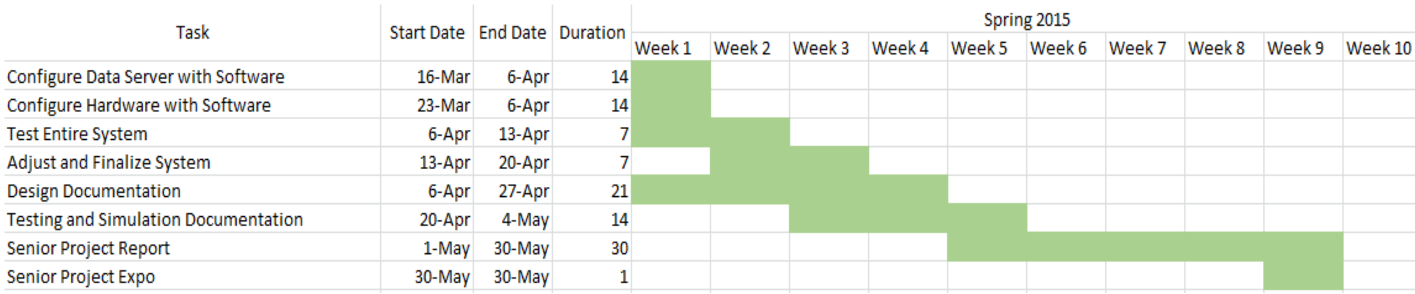

Figure 08c: Spring 2015 Gantt Chart

The cost of each part for the fully completed Wireless Mesh Network is detailed in the Table 06 below. We are comparing the cost of our product to the sensor probes from Ranch Systems. A four foot probe that measures the soil moisture is $1,045 [11].

Table 06: Cost estimation for project

Component	Price per unit	Quantity	Total Cost
TivaC Microcontroller (and accessories)	$19.99	1	$19.99
Temperature Sensors	$0.25	4	$1.00
Soil Moisture Sensors	$2.49	4	$9.96
Packaging	$35.78	1	$35.78
Zigbee Module (TI CC2530)	$75	1	$75
Battery	$10.00	1	$10
Booster Pack	$20	1	$20
Total			$171.73

Labor Estimation

With this project, much of the time is dedicated to designing and testing the whole device so that it is working within the whole network. Of the cost, labor costs would be included within the price. Typically, standard engineers are paid around $20-30/hr. The time spent building and testing the whole wireless mesh network would range 400- 500 man hours. Using the equation from Ford, Chapter 10, the optimal cost would be ($cost_a$) 400 hrs. x $20 = $8,000 [5]. The least optimal cost would be ($cost_b$) 500 hrs. x $30 = $15,000. Between these two extremes, the cost would be ($cost_m$) 450 hrs. x $25 = $11,250. Using the Ford's equation [5], the result labor estimation is:

$$Cost = \frac{costb + 4costm + costa}{6} = \$11,333$$

4. If Manufactured on a Commercial Basis

If this network was to be manufactured on a commercial basis, it would be depicted as seen in the following table. The cost would be represented based on the number of nodes needed for a given farm/ranch. The more nodes present the more of an accurate reading is given by the allotted area. The more nodes there are the higher the cost will be.

Table 07: Long Term Cost Analysis

Manufacturing Estimation	Estimated Cost
Estimated number of devices sold per year	100
Estimated Manufacturing cost for each device	$171.73 +50x x=number of nodes
Estimated Purchase price for each device	$200 +50x x=number of nodes
Estimated Profit per year	$5,000

Estimated cost for Operation	$0.05/ hr

5. Environmental

The environmental impacts of this project are highly beneficial. The data gathered from these networks will help users cultivate their farms based on the trees' needs. This way, the trees won't suffer because of too little water and the farmers won't be wasting unnecessary water. Also, the atmospheric data will help farmers prepare for harmful weather conditions, like frost or high winds. However, manufacturing and deployment of these systems will have a detrimental environmental impact. The systems will need electricity to run, but low power components are considered in the design. The manufacturing of the boards and sensors uses a substantial amount of metals like silicon.

6. Manufacturability

This product design will be taking already manufactured components and configuring them together. Because the project is dependent on these existing manufacturers, the availability or price points of these components will affect our final products over time. For example, the microcontroller used is the Tiva C from Texas Instruments. If Texas Instruments stopped making these microcontrollers or stopped supporting them, developing these networks will become difficult. The microcontroller will have to be replaced and consequently, some functionality may decrease. Unfortunately, we figure that Texas Instruments updates their product line and we may have to transition into another microcontroller if they phase out our existing microcontroller.

7. Sustainability

The network will be designed with sustainability as a high priority. To be considered for IEEE 802.15.4, the battery life must be very long (from a couple of months to several years. Since we are using a rechargeable li-ion battery, the users are left with a product that makes them confident of their decisions associated with care for their orchards with management of the product itself.

However, the components may need to be switched out after five years of use due to deterioration. To increase this period of time, the sensor module, when deployed will have to be hermetically sealed to be waterproof.

After deployment, there can be some upgrades made to improve the sustainability of the system. For example, we could design our own microcontroller for optimal performance on our certain tasks. Challenges to implement this upgrade will be increased cost, additional design time, and complex implementation into existing networks.

8. Ethical

According to the IEEE code of ethics [4], engineers can only “undertake technological tasks for others only if qualified by training or experience”. The subjective nature of this statement could pose some problems in the future. One could argue that our education is adequate experience to design the network. However, if a problem arises, one could argue that with even more experience, the engineer working could have expected and avoided the situation.

If a problem is predicted to happen in the future, one must “avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist”. Even though this will set the timeline back to come up with another design, pinpointing future problems will save subsequent issues with recall and reputation.

Since the functionality of this project is highly constrictive, misuse of this product will not be a problem. The data transmitted over frequency bands could be hacked by other receivers, but the sent data isn’t critical to the company or user.

9. Health and Safety

The wireless network has very little health concerns associated with it. The data transmitted is sent at a harmless frequency. Manufacturing and configuration of the product is very harmless. Testing of the system may pose some consideration because of possibilities of high current and therefore high power output.

10. **Social and Political**

This product raises political concerns with the stakeholders of this project. The users want a product that is lower in cost when compared to our competition. We must be able to provide them with a low cost alternative that has comparable performance. If we fail to bring this, our customers are left with no solution.

11. **Development**

During the development process, design will be directed according to predefined specifications given by IEEE protocol. This enables creative solutions to be engineered, such as different components or manipulating code.

One solution is the implementation of a long lasting power source. The battery life depends on the usage of the system. The type of battery, in this case li-ion, ensures that the system is low power and sustainable.