ZigBee Wireless Soil Moisture Sensor Design for Vineyard Management System

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I must also thank AUT technician Brett Holden who guided and advised me with analogue circuit design.

Finally, thanks to my friends and family for their support during the course of my research.

Statement of Originality

‘I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for qualification of any other degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made in the acknowledgements.’

Achala Perera
31/05/ 2010

Consequential Research Outputs

During the undertaking of this thesis, the writer had following research outputs.

Publications

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Ghobakhlou A, Sallis P, Diegel O, Zandi S and Perera A (2009). Wireless Sensor Networks for Environmental Data Monitoring. 8th Annual IEEE Sensors Conference Christchurch October 25-28, 2009

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Abstract

The soil moisture level is one of the critical aspects, which controls the quality of the grapes grown in vineyards. The main objective of this research is to investigate the development of a low cost soil moisture sensor, which can be used in a ZigBee mesh network.

ZigBee is a new mesh networking standard, which places emphasis on low cost sensor networks and energy conservation. The development focus for ZigBee is remote monitoring and control applications. Manufacturers are still improving their ZigBee devices and ZigBee software stacks.

The ZigBee based Texas Instruments CC2430 microcontroller was selected as the wireless sensor hardware for this research. Micro climate weather station was designed to monitor the vineyard environmental data like temperature, pressure, sunlight, humidity, leaf wetness and soil moisture and temperature. The wireless soil moisture sensor is one main component of the micro climate weather station.

The two probe soil moisture sensor uses the basic principle of a series fed Hartley oscillator frequency shift due to the varying dielectric constant of the soil according to the soil Volumetric Water Content (VWC). When the soil VWC increases, the dielectric constant also increases as the oscillator frequency decreases. This basic principle is used measure the soil moisture content.

Both the soil moisture sensor and micro climate weather station have been developed and tested with the ZigBee mesh network topology. The soil moisture sensor was tested and calibrated, using two different soil types.

This research has successfully achieved its objectives and identifies areas for future development. The third version of the micro climate weather station is under development with the focus on modular design, and a new sensor management system to improve energy conservation.

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1 Introduction

Wireless Sensor Networks (WSN) have been the subject of research in various domains over the past few years and deployed in numerous application areas. WSN is seen as one of the most promising contemporary technologies for bridging the physical and virtual world thus, enabling them to interact. A WSN is composed of a number of sensor nodes, which are usually deployed in a region to observe particular phenomena in a geospatial domain. Sensor nodes are small stand alone embedded devices that are designed to perform specified simple computation and to send and receive data. They have attached to them a number of sensors, gathering data from the local environment that is being monitored. WSNs have been employed in both military and civilian applications such as target tracking, habitant monitoring, environmental contaminant detection and precision agriculture [1, 2].

The work described in this research is a realisation of a concept outlined in Eno-Humanas project [3]. It is a system for gathering (sensing) and analysing climate, atmosphere, plant and soil data. It is specifically designed for microclimate analysis in vineyards and other agricultural/horticultural environments. This research has produced a prototype in order to demonstrate how state-of-the-art devices could be used in precision viticulture as a management tool to improve crop yield quantity and crop quality in a vineyard.

1.1 Problem Description

The main objective of this research is to design a vineyard monitoring and management system, which can be used to reduce the operating cost of the vineyard, and to increase and predict the quality of the yield.

Moreover increasing population and deforestation is causing tremendous pressure on the world's water resources. Water is one of the most precious commodities in the world and it needs to be preserved for future generations. Irrigation is one of the main water consuming industries. It has been estimated that the world's irrigation efficiency is less than 40 percent [4]. In order to improve irrigation efficiency, it is important to monitor the soil Volumetric

Water Content (VWC) to avoid over watering plants. Over watering also causes fungal diseases and other infections in plants. Therefore irrigation monitoring is one of the critical factors in a vineyard management system.

Extreme weather conditions such as frost cause crop losses of 50%. Therefore early frost prediction is one of the useful outcomes of vineyard monitoring. Several environmental conditions need to be measured in order to successfully predict frost conditions.

The objective for this thesis was to investigate and design a low cost soil moisture sensor for irrigation management in the vineyard.

2 Literature Review

2.1 Wireless Sensor Network Protocols

WSN is rapidly developing in the automotive industry, agricultural, industrial monitoring and many other areas. This technology has no connectors, so it provides safe/flexible connectivity, improved resources sharing, easy installation and mobility [5]. The other advantage is that it requires low power levels, so it can last for a longer period of time [5]. Two major protocols are used in low power, low data rate personal area wireless networking, IEEE 802.15.4 and the ZigBee stack.

2.1.1 IEEE 802.15.4 Protocol

The IEEE 802.15.4 is a part of the IEEE family of standards for the physical and link layers for Wireless Personal Area Networks (WPANs). The main focus of IEEE 802.15.4 is low data rate WPANs, with low complexity and low power consumption requirements. IEEE 802.15.4 uses device classification to reduce the complexity of the nodes. The standard classifies two types of devices to reduce complexity, a full function device (FFD) and a reduced function device (RFD). The RFD can only communicate with FFDs, but the FFD can communicate with both FFDs and RFDs. The IEEE 802.15.4 supports two Physical Layer (PHY) options. The 868/915MHz PHY known as low-band uses binary phase shift keying (BPSK) modulation whereas the 2.4 GHz PHY (high band) uses Offset Quadrature Phase Shift Keying (O-QPSK) modulation.

The IEEE 802.15.4 standard also uses two types of channel access method depending upon network configuration. When non-beacon mode is enabled the network uses an un-slotted carrier sense multiple access with collision avoidance (CSMA-CA) channel access method. The beacon method uses an optional slotted CSMA-CA channel access method.

The superframe structure is only used in beacon mode. In non beacon mode superframe structure is disabled and nodes compete for channel access via CSMA/CA. The superframe is divided into 16 slots, the first slot contains the transmitting beacon and he other 15 slots are used for node communication. Coordinator node defines the structure of the superframe, with two sections: Connection Access Period (CAP) and Connection Free Period (CFP). The basic superframe structure is shown in Figure 1. In a larger network, when the traffic volume is higher, most of the time slots are used for CAP, not for CFP [6]. Therefore this mode is not suitable for a network which involves a larger number of nodes.

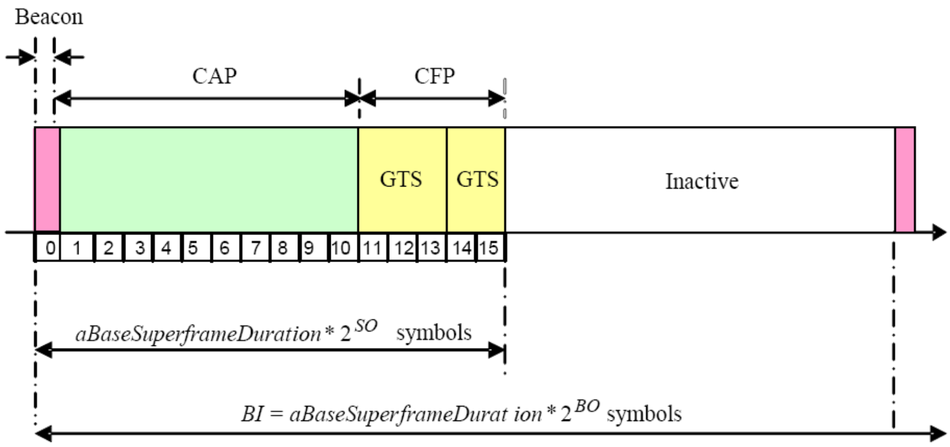


Figure 1: IEEE 802.15.4 Superframe Structure [7]

A non beacon network is more useable than the beacon enabled network. The Media Access Control (MAC) of the non-beacon mode is contention based CSMA/CA. Therefore typically most of the receiver nodes are continuously active. This requires a more robust power supply, but it allows for networks where nodes can receive and transmit data continuously. For larger networks like this vineyard monitoring system, the non beacon mode enabled network is more suitable.

IEEE 802.15.4 networks can be separated into two main topologies, star and peer-to-peer. A variation of peer-to-peer allows a third topology, which is called cluster tree.

Compared to the other two topologies, the star topology has the most structured configuration. The Personal Area Network (PAN) coordinator node always sits in the centre of the network. All the other nodes need to communicate via the PAN coordinator node. The PAN Coordinator node relays messages to other nodes in the network. Direct intercommunication between other nodes is not allowed (refer to Figure 2).

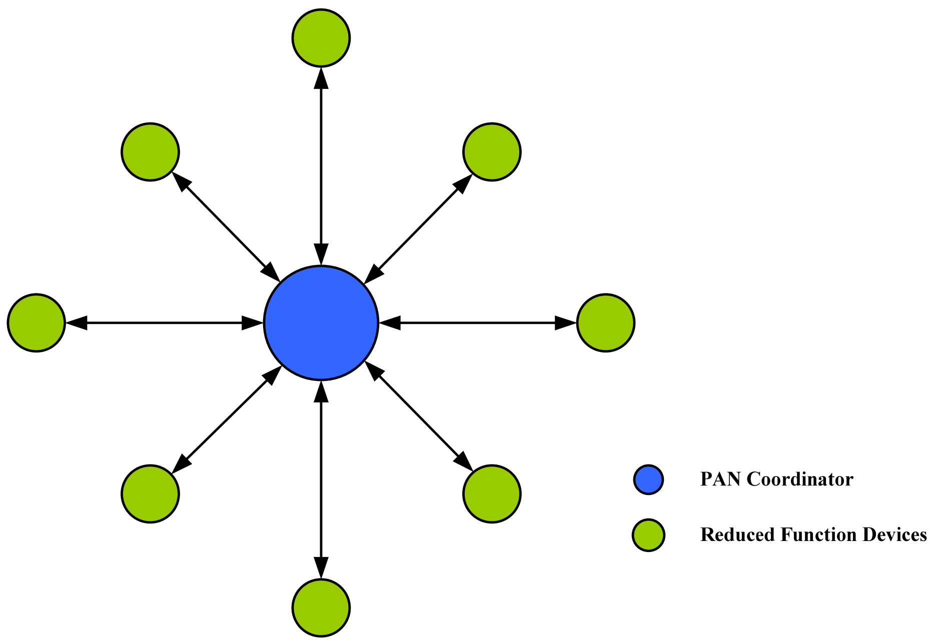


Figure 2: Star Network Topology

The peer-to-peer topology consists of three different types of nodes: PAN coordinator, full function node and reduced function nodes. In the peer-to-peer topology, an arbitrary array of connections can be created between full function devices and the PAN coordinator. Since a network layer is not defined in the standard, routing is not directly supported (refer to Figure 1 and Figure 3).

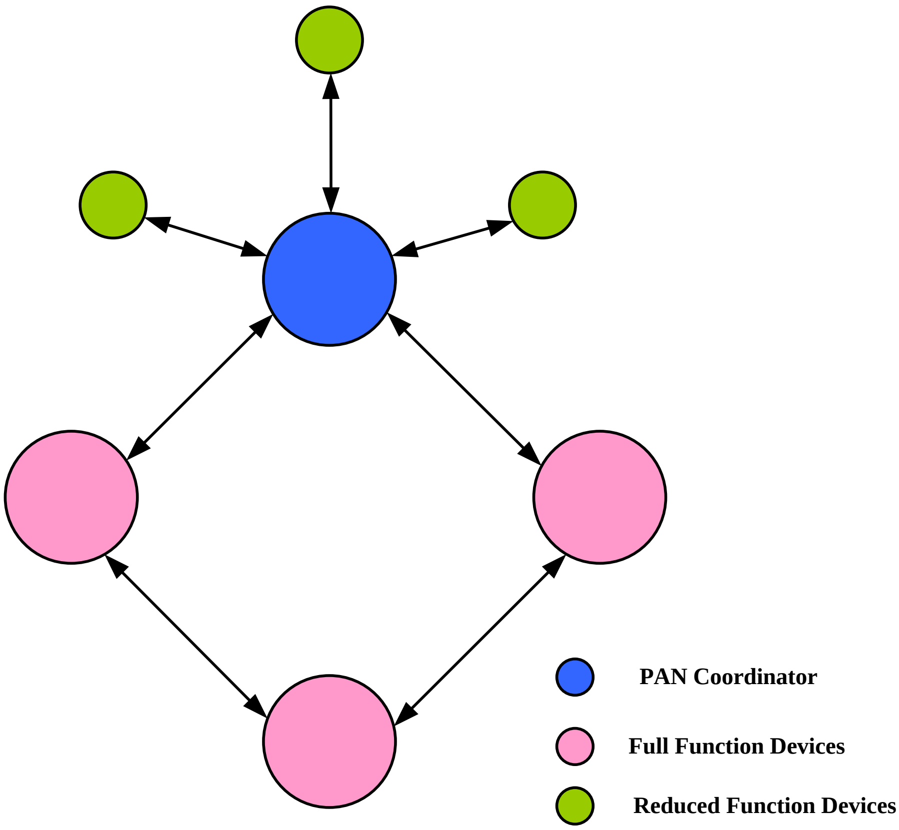


Figure 3: Peer-to-Peer Topology

The cluster tree topology is a special case of the peer-to-peer topology. This based on RFDs only can communicate with FFDs. Majority of devices in cluster trees are FFDs (refer to Figure 4).

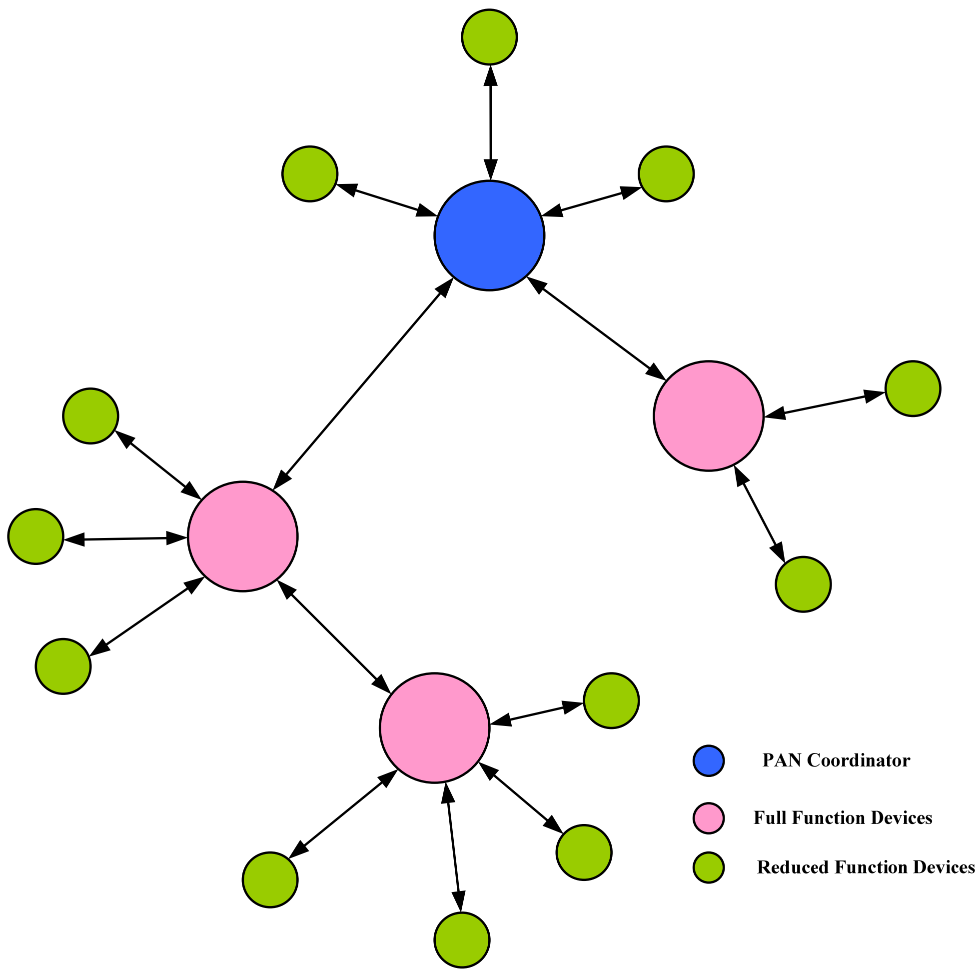


Figure 4: Cluster Tree Topology

2.1.2 ZigBee Protocol

The ZigBee network layer stack sits on top of IEEE 802.15.4 standard Medium Access Control (MAC) and PHY layers (refer to Figure 5). The MAC and PHY layers contain the RF and communication components that communicate with other devices. The ZigBee stack contains the networking layer, an application support sub-layer and a security service provider (SSP) [8].

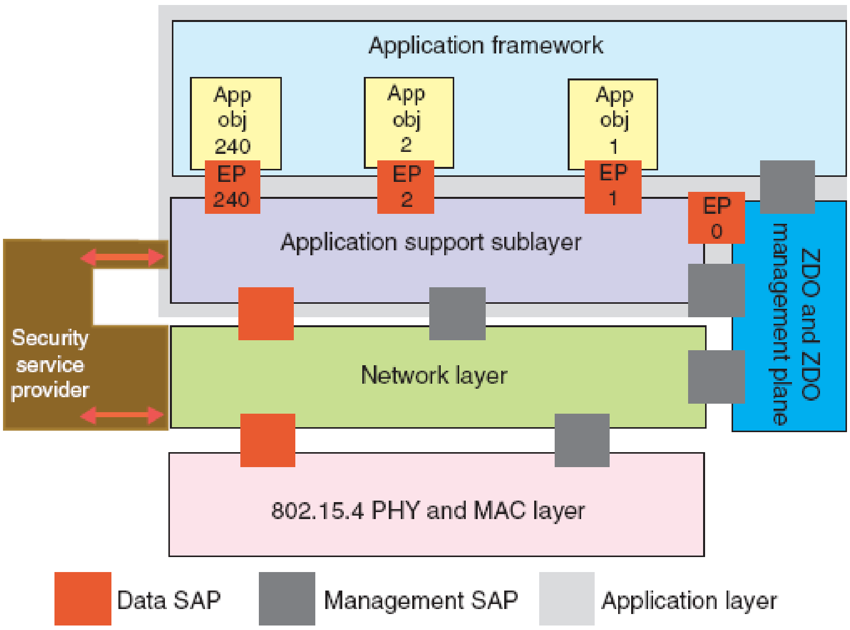


Figure 5: ZigBee Stack Layer [9]

The IEEE 802.15.4 and ZigBee protocols have their own limitation and advantages. The main limitation for both protocols is a low data rate (narrower bandwidth) (refer to Figure 6). Therefore these protocols are only suitable for low data transmission applications.

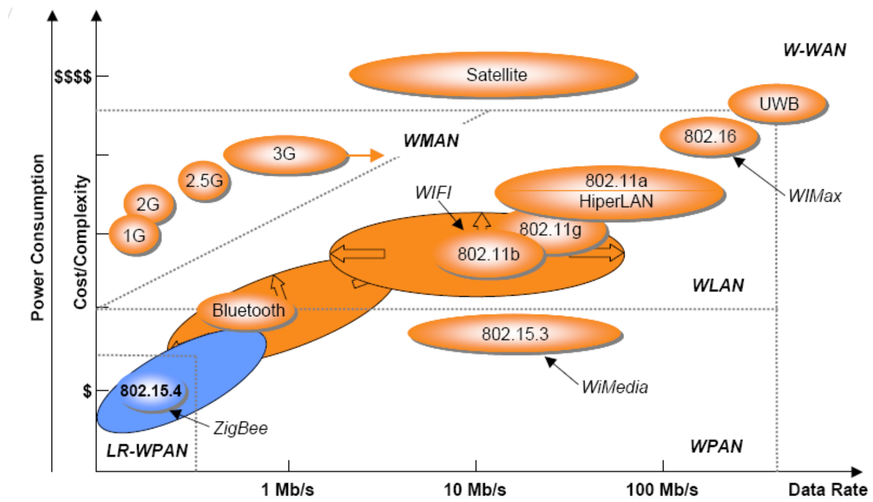


Figure 6: Standard Technology Map [5]

As shown on Figure 6, as the data rate is increased, the power consumption, cost and complexity of the system increase. Since sensor nodes are located remotely, power consumption needs to be minimal. Battery operation is usually the preferred option. Moreover, sensor data does not require a wide bandwidth. Therefore, according to the Figure 6 above, the most suitable protocol for a small sensor network is ZigBee.

The three main network topologies used in ZigBee wireless networking are star, point to point and mesh networks (refer to Figure 2 and Figure 7). These topologies can be used in different environments and situations.

The point to point system is mostly used to replace a single communication cable. Point to point network can work adequately, when two end points are located close to each other [10].

The star topology is also known as a point to multipoint wireless system. This system is mostly based on IEEE 802.11 or Bluetooth. The system has one main base station, which controls the communication with all the other end nodes. The reliability of this network is dependent upon the quality of the RF link between the base station and each end node. The main problem with this system is that in industrial applications it is hard to find a suitable place for the base station in order to communicate with each end node [10].

The mesh topology is also called a peer-to-peer system. This system is an ad hoc multi hop system. In a mesh network based on the ZigBee protocol, each node can be used to send and receive data. Therefore data will reach its ultimate destination reliably, via intermediate nodes (refer to Figure 7) [10]. The network consists of multiple redundant communication paths.

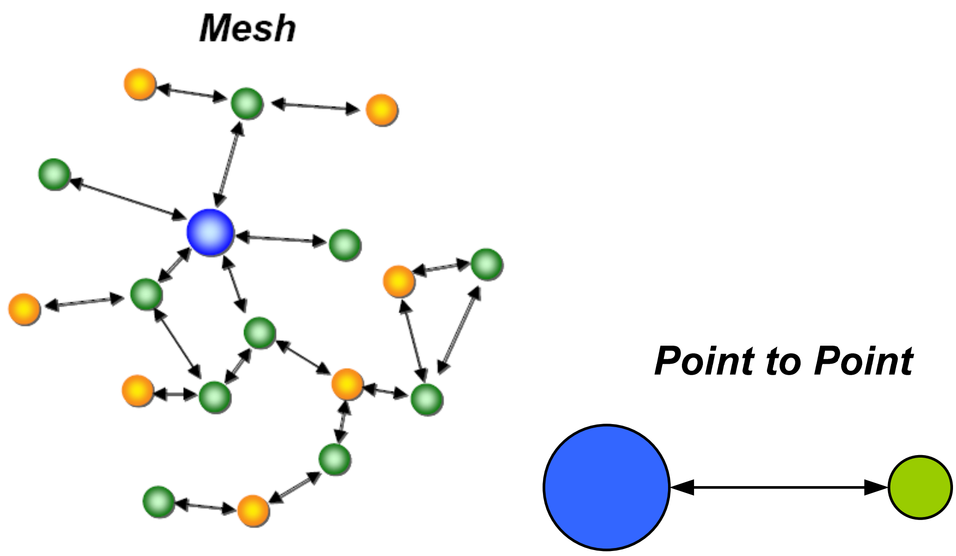


Figure 7: ZigBee Topologies [5]

The mesh network has the important properties, it is self-configuring, self-healing and scalable. ZigBee mesh network forms itself, it does not require manual configuration. The network identifies new nodes and automatically includes them in the network [10]. Moreover if a node stops functioning, the network re-routs messages through alternative paths to avoid this node. According to the ZigBee standard, a mesh network may contain up to 65,536 network nodes (clients) [10]. The

Table 1 below compares the above key points for each network topology.

Topology	Reliability	Adaptability	Scalability
Point-to-Point	High	Low	None (2 endpoints)
Star Network	Low	Low	Moderate (7-30 endpoints)
Mesh Network	High	High	Yes (1000s of endpoints)

Table 1: Network Topology Suitability in Industrial Applications [10]

2.2 Currently Available ZigBee Devices

At present there are only a few devices in the market, which have built in radio for wireless sensor networking. Some manufacturers are currently using external wireless radio semiconductor devices, with separate microcontrollers to create wireless sensor network devices. In the last few years Atmel and Texas Instrument (TI) have been revolutionising the wireless microcontroller device market by introducing an inbuilt radio module with the microcontroller, controlled via microcontroller registers. These new devices have low power consumption and longer data communication distance. The other main advantage of these devices is that a micro strip line Printed Circuit Board (PCB) antenna can be used to transmit and receive the data.

2.2.1 Atmel

Atmel produces popular ZigBee transceivers, which can be used with external an Atmel microcontroller or third-party microcontrollers. Recently Atmel has started producing a System on Chip (SoC), that combines one of their popular AVR 8 bit ATmega128 microcontrollers and an AT86RF230 transceiver in a single silicon device. The AT86RF230 transceiver has excellent range and low power consumption compared to other transceivers in the market. The main drawback of the Atmel ZigBee solution is its limited ZigBee stack. This limitation will increase the application layer software development time.

Figure 8: Atmel AT86RF230 Development Tool

2.2.2 Texas Instrument (Chipcon)

Chipcon is one of the most popular SoC ZigBee devices in the market. Texas Instrument (TI) is the first manufacturer to combine the 8051 microcontroller architecture with the Chipcon ZigBee transceiver. This revolution made the TI wireless device the most popular among wireless system designers. Chipcon devices provide reasonable RF range and power consumption performance. The main advantage of TI devices is they provide a full featured ZigBee and IEEE 802.15.4 MAC software layer, with most of the source code. This is very attractive for software development and research applications.

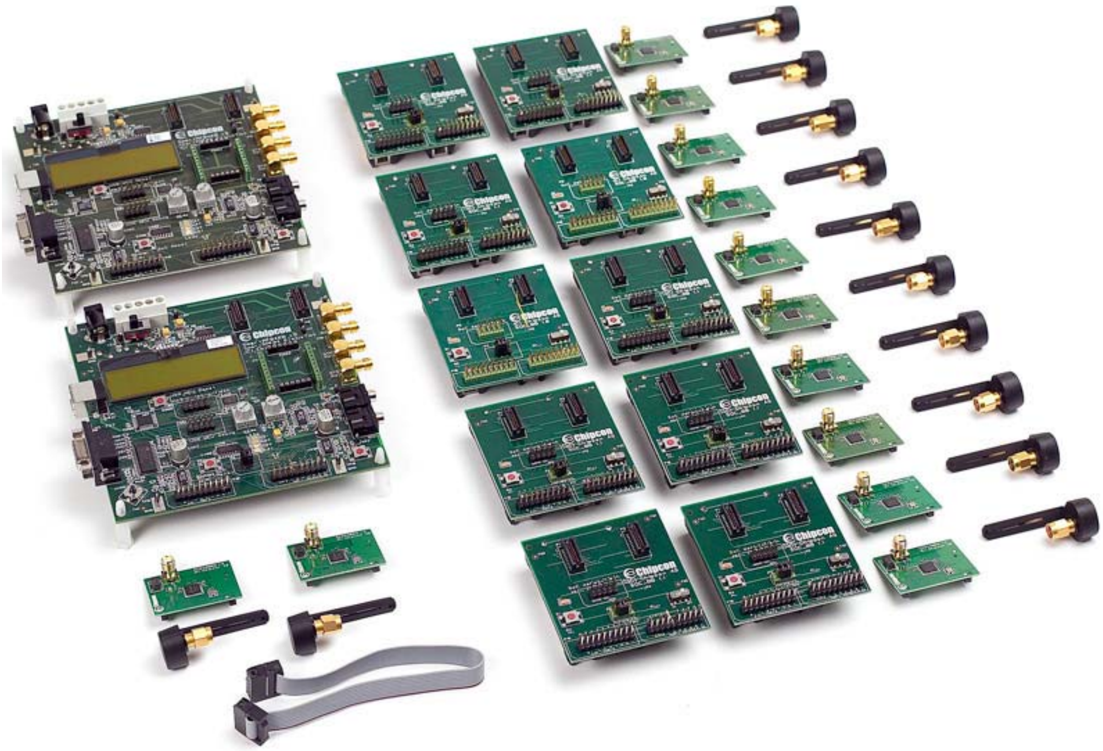


Figure 9: CC243x ZigBee Development Tool

2.2.3 Meshnetics

Meshnetics has several ZigBee products in the market. All these devices are Atmel hardware based modules. The main advantage of the Meshnetics is they provide a more complete ZigBee stack compared to the Atmel stack. Moreover the Meshnetics ZigBee stack comes with a real time operating system (RTOS) to reduce the software development time and the complexity of introducing user defined application layer tasks. The main disadvantage of the supplied ZigBee stack is that most of the source code is hidden in pre-complied libraries. When developing a normal application this is not an issue, but due to unforeseen circumstances if the software developer is required to modify or change the functionality of the stack, this could create a problem.

Figure 10: Meshnetic ZigBee Development Tools

2.2.4 Microchip

Microchip is currently trying to enter the wireless transceiver market. At present they have a limited number of ZigBee transceivers. These transceivers have tolerable RF performance range and power consumption. In general the main advantage of Microchip devices is they normally provide all the source code to software developers. Software developers have full access to their ZigBee stack. This makes the development time faster. However the main disadvantage of the Microchip ZigBee stack is it has limited functionality compared with the TI or Meshnetics ZigBee stack.

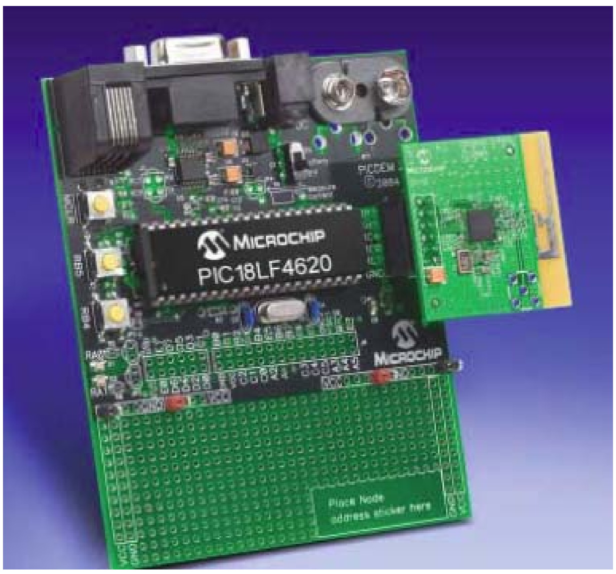


Figure 11: Microchip ZigBee Development Tool

Manufacturer	Product	ROM (KB)	Ram	Transmit Power	Receiver Sensitivity	TX Current	RX Current	Sleep Current
Atmel	AT86RF230	NA	NA	3dBm	-101dBm	16.5mA	15.5mA	20nA
	ATmega128 RZAV	128	8KB	3dBm	-101dBm	26.5mA	25.5mA	1.02uA
Meshnetics	MNZB-24-A2	128	8K	3dBm	-101dBm	18mA	19mA	6uA
	MNZB-A24-UFL	128	8K	20dBm	-104dBm	50mA	23mA	6uA
Chipcon	CC2430	128	8K	0dBm	-95dBm	26.9mA	26.7mA	0.5uA
	CC2420	NA	NA	0dBm	-95dBm	17.4mA	18.8mA	20nA
Microchip	MRF24J40	NA	NA	0dBm	-95dBm	23mA	19mA	2uA

Table 2: Current ZigBee Transceivers

The Chipcon CC2430 ZigBee microcontroller transceiver was selected for this research. The main reason are for this selection was that the CC2430 has a built-in microcontroller, so the final design does not require a separate microcontroller and ZigBee transceiver. The CC2430 microcontrollers are also cheaper than most other ZigBee solution devices. The CC2430 comes with a free full ZigBee stack and 802.15.4 MAC layer software stack with source code. Finally it has reasonable RF performance and acceptable power consumption.

2.3 Soil Moisture Monitoring Techniques

There are several methods currently used to measure soil moisture content. Some methods are more precise than the others. Similarly some techniques are more expensive and complicated than others. In order to achieve a suitable compromise of complexity, price and accuracy, it is important to analyse the advantages and disadvantages of each technique. The other important factor is the suitability of the selection for a specific application and environment.

2.3.1 Gravimetric Technique (Oven dry and weigh)

This is the simplest and most accurate technique for any soil sample. The basic principle is to dry a soil sample in an oven at 105 °C for 24 hours to determine the soil moisture content. The soil moisture content equals to the initial field soil weight less the oven dry weight. The main advantages are it is relatively inexpensive, really simple, does not require specialised equipment and is highly accurate. The disadvantages are it is time consuming and labour intensive. The accuracy of the experiment depends on the accuracy of the scale. Moreover this technique is not suitable for measuring larger areas with larger sample sets, like a vineyard.

2.3.2 Dielectric Constant Soil Moisture Probe and Meter

There are two techniques used to measure the soil dielectric constant, Time Domain Reflectometer (TDR) and Frequency Domain Reflectometer (FDR). Both techniques measure the capacitance of a non conductor (in this case soil) using high frequency electromagnetic waves or pulses. The result can be related to soil moisture content. The difference between these techniques is the TDR measures the time taken for an electromagnetic wave to travel through the soil between the probe pins, whereas FDR uses a radio frequency wave to measure the soil capacitance.

The advantages of these types of soil measuring techniques are that they are relatively accurate (±1-2%) and can provide a direct read out of volumetric soil moisture percentage or continuous readings if required by a data logger or sensor network. These systems are relatively unaffected by soil mineralogy [11]. The TDR technique is more accurate and less affected by soil minerals [11], while FDR can detect bound water in fine soil particles. In general TDR instruments are considerably more expensive than FDR. Also the electronics for TDR is more complicated than for the FDR technique. Generally the FDR technique is preferable due to its reasonable accuracy, affordability and ease of use [11].

The disadvantages are these instruments are more expensive than most other techniques, reading error occur if good contact is not made with soil, and probes can be damaged in rocky soils.

Figure 12: TDR and FDR Sensor Probes [12]

2.3.3 Neutron Probe

This probe measures the slowdown of fast neutrons emitted into the soil resulting from collision with soil water molecular hydrogen (refer to Figure 13) [13]. Therefore it measures the total amount of water in a soil, based on the rate of neuron slowdown. The advantage of this technique is allows a rapid, accurate, repeatable measurement of soil moisture content in different depths and locations. The major disadvantages are the use of radioactive material requiring a licensed and extensively trained operator, the high equipment cost ($3,500–$4,500) and extensive calibration for each site.

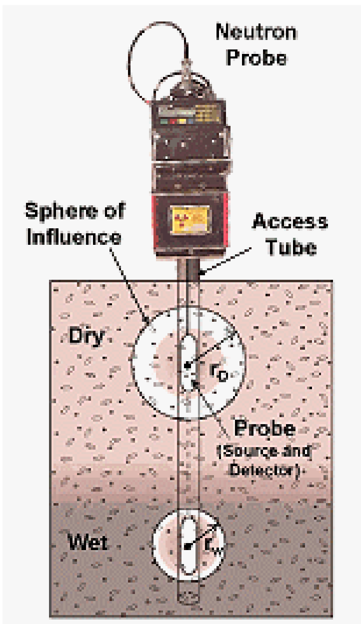


Figure 13: Neutron Probe [12]

2.3.4 Tensionmeter

A tensiometer is an airtight, hollow tube filled with water. A porous ceramic cup is attached to the end of the tube inserted into the soil and a vacuum gauge is attached to the upper end. This technique measures the soil moisture tension, an index of how tightly water is held in the soil. A soil moisture re-tension curve is developed for each of the soil sample to determine the soil water content.

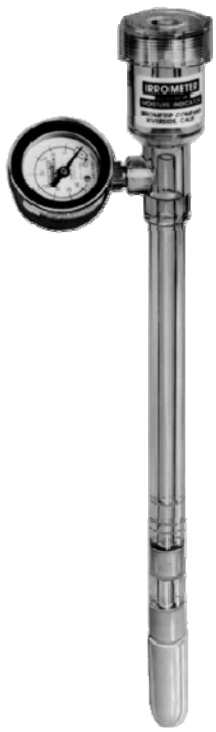


Figure 14: Tensiometer [12]

The main advantage of this technique is that the tensiometer is not affected by the amount of salts dissolved in the soil water. It measures soil moisture tension with reasonable accuracy in the wet range. The main disadvantage is it only operates between saturation and about –70kPa. Therefore it is not suitable for measuring dry soils.

2.3.5 Resistive Soil Moisture Sensor

The fundamental theory of the soil moisture sensor is to use a voltage divider circuit to read the voltage drop across the soil sample and convert the voltage readings to moisture value. When the soil moisture level increases the impedance decreases [14]. The schematic is shown below Figure 15.

Figure 15 used an AC voltage to avoid the polarization of the soil sample. The main advantage of this method is the electronics is really simple and the total cost of the system is low. Therefore it is suitable for data loggers and wireless sensor networks. The main disadvantage is the system has poor accuracy. The final readings are affected by the soil mineralogy. Moreover system overall response time is slow due to the granular matrix around the probe.

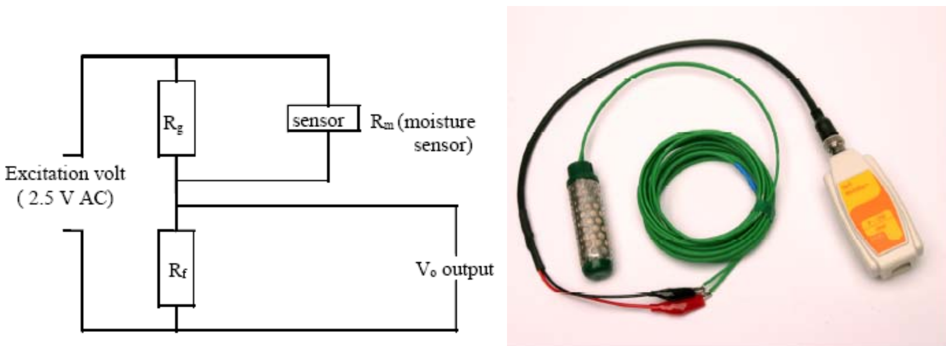


Figure 15: Impedance Base Moisture Sensor [14]

3 Vineyard Monitoring and Management

The recent introduction of wireless sensor networks facilitates the monitoring of a vineyard's environmental conditions. It enables growers to quantify spatial variation in a vineyard and different regions of the vineyard can be mapped according to their yields [15]. Location awareness and WSN technology together with computer based geographical information systems (GIS), and the capability to process yield productivity related data, has assisted the gradual increase in *precision agriculture*. In the grape and wine industry, *precision viticulture* can be characterised as monitoring and managing spatial differences in yield and quality within single vineyards.

The wireless soil moisture monitoring application is one component of the micro climate vineyard monitoring and management weather station. This research was funded by Geoinformatics Research Centre. Currently strong interest in this technology is building at different vineyard all around the world. Most vineyard owners are keen to know their vineyard environmental and soil data, to compare result with different vineyard conditions all round the world. By comparing the historical environmental condition and soil condition they can predict the quality and productivity of the yield. At present, the first version of the system is installed in New Zealand and Chile, with Japan to be added in the future.

3.1 System Architecture

The proposed WSN system [16, 17] consists of sensor nodes located in critical locations within vineyards for collecting weather, atmospheric and environmental data as well as plant related data such as leaf wetness and sap flow. Figure 16 shows the system architecture consists of three layers namely, sensor layer, server layer and application layer.

Sensor layer: This layer consists of all the wireless sensor nodes and a Base Station (BS). Each node has one or more sensors plugged into the hardware device with a transmitter, power supply (usually a small battery) and microcontroller. The nodes are distributed over an area of interest uniquely arranged as required provided the distance between the sensor devices does not exceed the maximum communication range. Therefore, energy optimized routing becomes essential. Data transmission from sensor nodes to the BS depends on the application: continuous, event driven, query-driven or hybrid. In the continuous approach, data is transmitted to the BS periodically according to predetermined intervals. In the query and event driven models, data is transmitted when an event takes place or a query is generated from the BS. The hybrid model uses combinations of these approaches to transmit data from sensor nodes to the BS. Various types of routing protocols such as data centric, hierarchical and location based protocols are available [17, 18].

Server layer: Data are sent to the data server from the BS through the internet. Two main tasks performed by the data server are to:

1. Obtain and process data from the BS.

2. Populate the database with WSN data and enable the application layer to access WSN data.

The server layer also deals with on-time data delivery from the BS and generates alarms when an undesirable events take place.

Application layer: This layer allows users of the system to have remote access to WSN data using web browsers. This provides a powerful tool to visualize real time WSN data and compare data from various nodes. In addition, the BS can be accessed remotely to modify sensor node configurations [17]. The windows based software was developed at the Geoinformatics Research Centre.

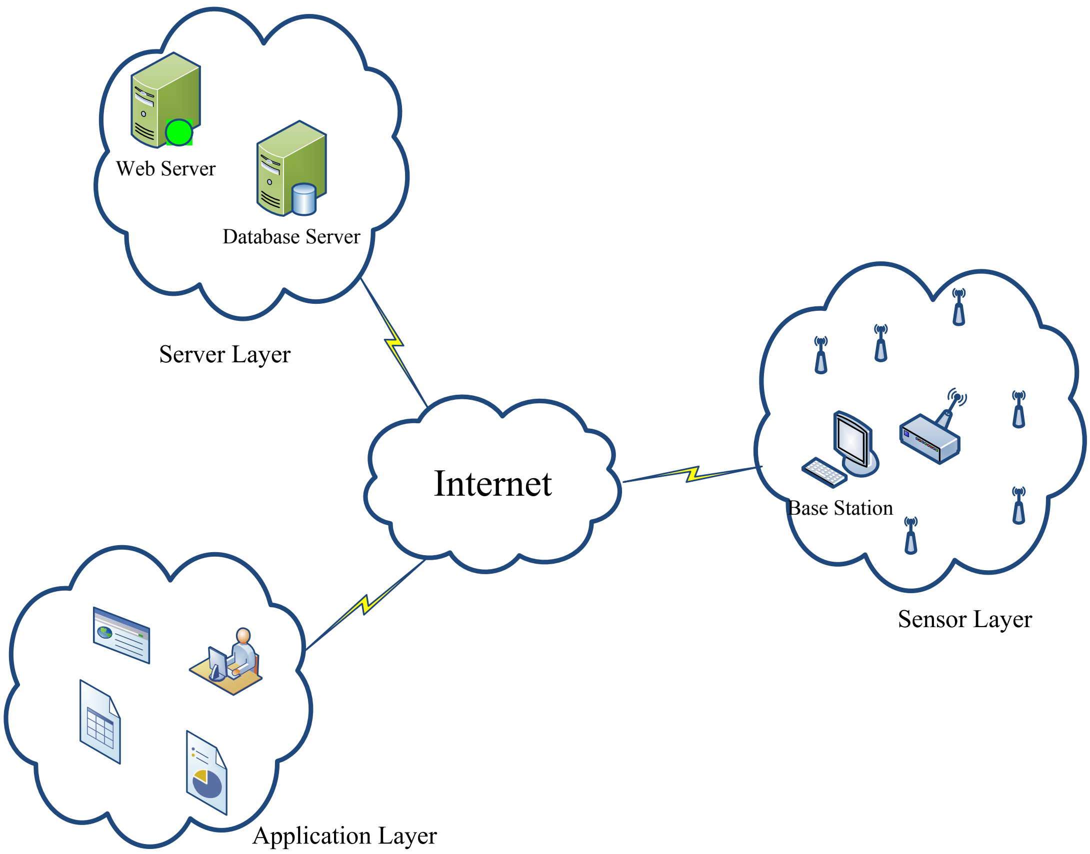


Figure 16: A schematic view of WSN architecture [17]

3.2 Micro Climate Weather Station

The main idea of the micro climate weather station is to collect the local weather conditions within the vineyard. Depending on different weather conditions, local weather can change rapidly. Therefore micro climate weather stations are installed every 100m^2, to monitor the weather condition. These small stations consist of various environmental and plant sensors to monitor the conditions. Each station contains sensors to measure pressure, humidity, wind speed, wind direction, temperature, sunlight, leaf wetness and soil moisture and temperature. Over time, the quality of the wine can be correlated with different environmental conditions and eventually the quality of the wine could be predicted from measured weather data. Micro climate weather stations can also be used to predict bad weather conditions, such as frost and dry soil.

3.2.1 Predicting Dew Point and Managing Frost

The dew point temperature is the temperature at which water vapour in the air will condense into dew, frost, or water droplets given a constant air pressure. It can be defined as the temperature at which the saturation vapour pressure and actual vapour pressure are equal. At this temperature the humidity is 100%. The dew point temperature together with relative humidity can be used to determine the moisture content in the air. A dew point temperature below 0 °C is referred to as the frost point because frost is produced when the air cools to that temperature [19]. When the frost point is about to occur it is important to take action beforehand otherwise severe damage may occur (refer to Figure 17).

Figure 17: Frost Damage [20]

The dew point temperature can be calculated at a particular temperature and pressure. By using Magnus formula [21] the saturation vapour pressure and dew point can be calculated, at a temperature T (in °C). The saturation vapour pressure EW (in hPa) over liquid water can be expressed as equation 1 [22].

$$EW = \alpha.e^{\left(\frac{\beta.T}{\lambda+T}\right)}$$

1

For the temperature range – 45°C to 60°C, the Magnus parameters are α = 6.112 hPa, β = 17.62 and λ = 243.12 °C. By restating equation 1 the dew point temperature Dp (in °C) can be calculated from vapour pressure E [22].

$$Dp = \frac{\lambda.\ln\left(\frac{E}{\alpha}\right)}{\beta - \ln\left(\frac{E}{\alpha}\right)}$$

2

*E = RH * (EW/100)*

3

Introducing the relative humidity RH (in %), equation 3 into equation 2 and using equation 1 leads to the calculation of the dew point Dp from temperature and relative humidity RH [22, 23].

$$Dp(T,RH) = \frac{\lambda.\left(\ln\left(\frac{RH}{100}\right) + \frac{\beta.T}{\lambda+T}\right)}{\beta - \left(\ln\left(\frac{RH}{100}\right) + \frac{\beta.T}{\lambda+T}\right)}$$

4

If the calculated dew point is less than 0 ̊ C and early frost warning can be issued to the vineyard owners, so they can arrange frost management techniques. There are four basic frost protection methods; proper site selection, heaters, wind and water sprinklers.

Site Selection: In order to minimise the frost protection cost later on, it is important to prepare and select the site appropriately. The planting lay out needs to be rows parallel to the prevailing direction of the cold air drift. It is important to prune the neighbouring trees and vines properly to avoid blocking air movement. To ensure good air drainage, natural swales and other air drainage pathways need to be opened and cleared [20].

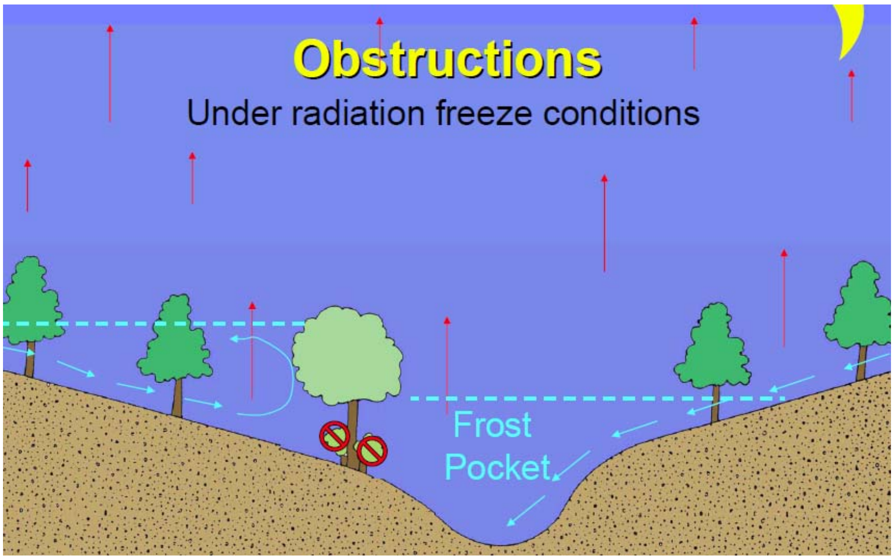


Figure 18: Clear out understory plants to improve drainage

Heaters: This is the only method, which is really effective in adverse freezing conditions (refer to Figure 19). The main draw back is that it is very expensive to setup the system and labour intensive. These heaters cost approximately $100 each. The fuel costs also come into consideration every time the heaters are used. The other major setback is these oil heaters are not environmentally friendly [20].

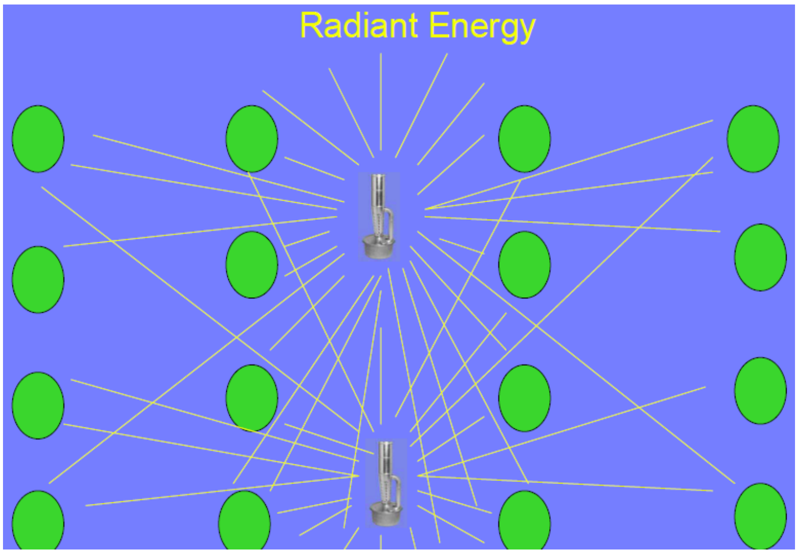


Figure 19: Plants must be in a direct line to the heat source

Wind Machine: The main aim of the wind machine is to draw down warmer air from above and mix it with the colder air to prevent stratification (refer to Figure 20). In order to make this technique effective, wind machines need to be started before the temperature drops below freezing point. One machine can protect up to 10 acres. These machines are not recommended to work below freezing conditions, because plant tissues are warmer than the air [20].

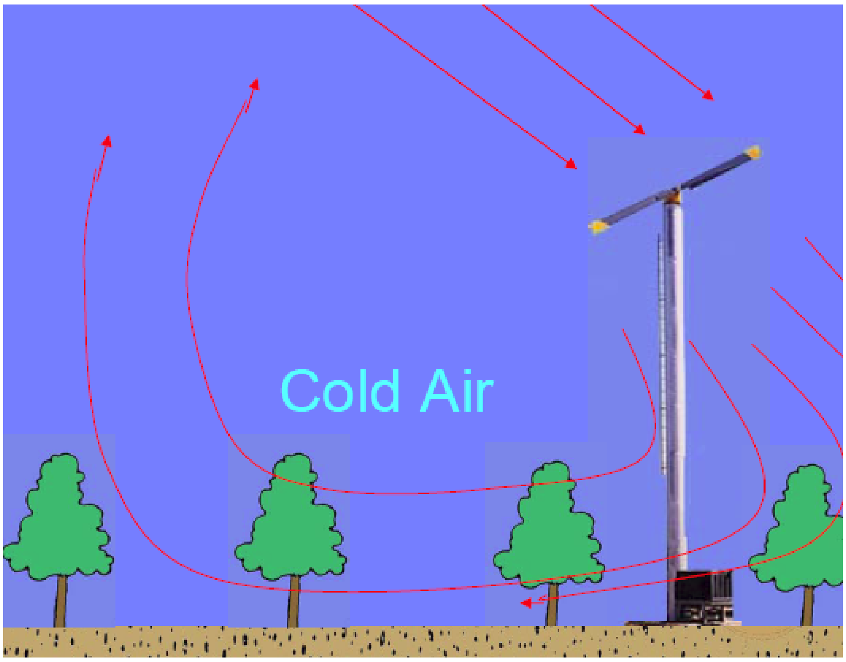


Figure 20: Wind Machine

Helicopters: The main advantage of the helicopter is height and differential of the inversion layer is not as critical as with a wind machine. Helicopters are very effective when hovering at slower speeds around 5 to 10 mph and can cover 40 to 50 acres (refer to Figure 21). In order to have maximum effect the helicopter needs to hover overhead every 5 to 6 minutes before air stratification reoccurs. The major set back is this method is very expensive, and on an average it costs more $500 per hour plus standby fee [20].

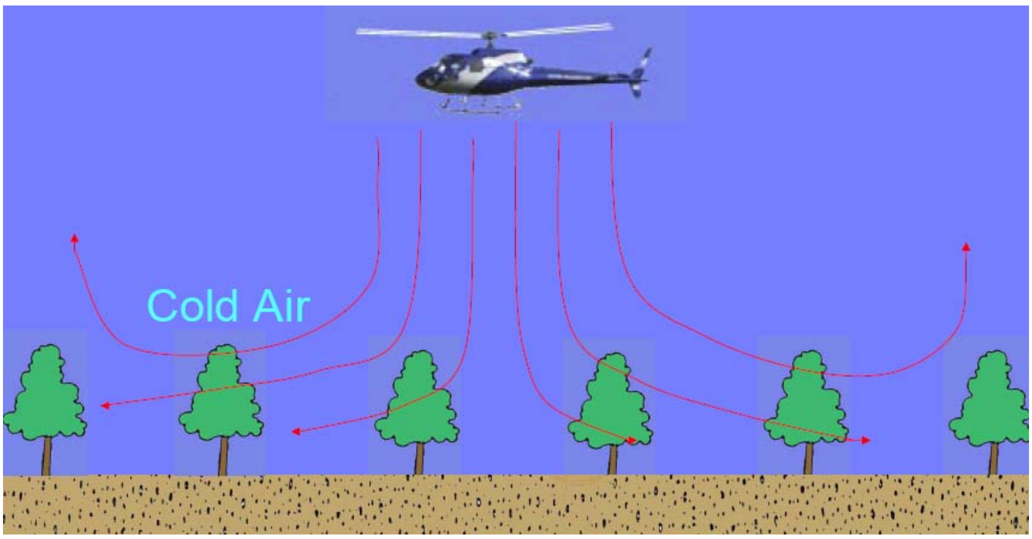


Figure 21: Helicopter Hovering Down Hot Air

Sprinklers: Relatively warm water gives up heat upon contact with the colder air and plant tissues (refer to Figure 22). The sprinkler system needs to be started before the temperature drops to freezing and run until the danger has passed. If the sprinklers are stopped before the danger, super cooling can occur and damage will be far more severe than if nothing was done. The overhead sprinkler systems are more effective. This method is cost effective and it can also be used for irrigation. In order to achieve optimum results, dew point prediction is critical [20].

Figure 22: Sprinkler System

3.2.2 Irrigation Management

It is important to know how much irrigation water is required to produce a quality yield for wine, dependent upon number of factors like site, the stage of vine growth, row spacing, size of the vine's canopy and amount of rainfall occurring during the growing season [24]. In irrigation management there are two important questions, which need to be answered in order to achieve optimum results. The questions are "*When to start?* and *How much water to apply?*". In order to remove guess work and achieve a useful decision outcome, soil moisture sensors can be used. Soil moisture sensors will provide the real time status of the soil moisture content and by using this information irrigation management can be optimised. Moreover money and water can be saved by optimising irrigation requirements. When selecting these environmental sensors it is important to consider the reaction time of the sensors, because some sensors have a very slow reaction time, i.e., by the time the sensor senses the moisture content, the irrigation system might have overwatered the plant.

The effect of irrigation on vine growth and fruit development can be best described by dividing the seasons into stages [25].

Stage One: Stage one occurs from after bud-break to the bloom period (refer to Figure 23: Bud-break Out to Bloom). The water requirement for grape vines is low during this period. Only 64mm is used during this 40 day period [26]. Usually moisture stored in the soil during the winter months is adequate to meet vineyard water requirements during this period. Even without any irrigation during spring, the grapevine does not show any symptoms of water stress. There are some exceptions, if the vineyard is on very sandy or shallow soil with limited soil water storage or with cover crops some irrigation is required to reduce the water stress. If sprinkler systems are used for irrigation during this stage, water stress can be minimised by diverting irrigation water used for frost protection [25].

Figure 23: Bud-break Out to Bloom

Stage Two: This stage covers from bloom to veraison (This is the stage when fruit begins to soften). During this stage the grapevine requires 102-178 mm of water [26]. Due to cell division and elongation in fruit proper irrigation management is critical [27]. During this stage, water stress causes reduction of berry size and yield [26, 28].

Figure 24: Veraison

Stage Tree: This stage covers from veraison to harvest. During this 60 day time period water usage of the grape wine is 178-229mm [26]. Raisin growers usually terminate the irrigation 2-6 week before harvest, depending upon soil type, to allow time for terrace preparation. Irrigation could be cut back to apply water stress to the grapevine to reduce the shoot growth between veraison and harvest [27]. During this period over irrigation can delay fruit maturity, encourage bunch rot, and delay or reduce wood maturity [25, 28].

Stage Four: The last stage covers from post harvest to leaf abscission. The length of this period defines the harvest date. Usually this period is 60-days, and during this time water usage is 102-152 mm [26]. The irrigation management system should try to regulate the irrigation to maintain the canopy but not encourage growth [24, 25, 28]. Excessive irrigation encourages vigorous growth or starts new growth after harvest and fail to ripen the wood. During this period mild to moderate water stress imposition could be useful to discourage shoot growth and encourage wood maturity [27]. But water stress should not impose grapevine defoliation. At the beginning of winter, when the temperature is too low to facilitate the shoot growth, heavy irrigation is suitable to replenish the soil water reservoir and satisfy the leaching requirement. Grapevines which are extremely water stressed during this period may have delayed shoot growth during the next cycle [25].

4 Objective and Methodology

The main aim of this research is to investigate and develop a wireless network for vineyard irrigation management and frost protection. This network is also used to collect other environmental and plant data such as humidity, pressure, temperature, leaf wetness, sunlight, soil moisture and soil temperature. The research is specifically focused on the development of an accurate, stable and fast reacting soil moisture sensor for irrigation management. It finally investigates the design of a micro climate weather station for vineyard management and an early frost prediction warning system.

4.1 Suitable Wireless Sensor Technology

H.R. Bogena [29] designed a soil moisture sensor network with ZigBee protocol. They describe, ZigBee as a group of high level communication protocols that uses small low power digital radio based on the IEEE 802.15.4 standard for personal area networks. It was found ZigBee had a low data rate transfer compared to WLAN networks, and that ZigBee is specially suitable for intermittent data transfer like wireless network applications [29].

S. Sulaiman et al [30] reported that their fringing electric field soil moisture sensor used the ZigBee protocol as a point to point data transmission system, in order to transmit the soil moisture readings to the computer.

Anurag D, Siuli Roy and Somprakash B [31] have developed personal a wireless sensor network for precision agricultural real time data monitoring. They have designed a wireless sensor network test bed for remote monitoring of agricultural parameters. The TI based CC2420 RF transceiver was used to create the ZigBee network. A cluster tree based network was created to collect the data.

Due to recent advances in wireless sensor technology and wireless sensor networking devices, development costs have decreased. It is also possible to engineer increasingly smaller devices in the radio spectrum [32]. According to

Luis Ruiz-Garcia [32], WSN eliminates all the problems with wires in a system. A multi hopping data transport system was used in this food container monitoring project.

Jzau-Sheng .L and Chun-Zu .L [33] used a SoC ZigBee solution to develop their agricultural monitoring system. Environmental data from the WSN was transmitted to the main computer via an Ethernet port. They have used the web server to store the data for final analysis. They used an external microcontroller with a 3160 module to develop point to point network topology to collect the environmental information [33].

By considering all these research outcomes, it was been shown that ZigBee is the most suitable WSN protocol for this application. The main attractive features of the ZigBee protocol are its low power and its ability to be used in various environmental conditions. As discussed in section 2.2, the TI CC2430 SoC ZigBee microcontroller was selected to form the WSN. Because vineyards have a large physical foot print to cover and mesh networks have not been used very much in vineyard monitoring and precision agricultural application, there is limited knowledge concerning ZigBee mesh networking and vineyard irrigation management in micro climate monitoring. In this research a ZigBee mesh network was used in conjunction with the TI CC2430 ZigBee microcontroller.

4.2 Soil Moisture Sensor Selection

According to the literature review, there are five techniques, which can be used to measure the soil moisture content. Therefore it is important to select a most accurate and sensitive technique to design an affordable soil moisture sensor for mass production in vineyard monitoring.

Valente, A., J. Boaventura Cunha, and C. Couto's [34] research used capacitance and heat pulse techniques to determine the soil water content. In their design, the sensor used the capacitance techniques as the primary method and heat pulse readings for calibration and fault detection purposes [34]. They have conducted several experiments on different soil samples and found this sensor could be applied effectively to measure soil moisture content. The main downside of this sensor design is that the heater requires a considerable amount of power. Therefore in remote application, such as vineyard irrigation monitoring this method could have a significant power management issue.

Y. Yamamoto and A. Ogawa [35] have designed a tensiometer. This sensor measures the water potential of the soil and converts the readings into soil moisture concentration. They have used this meter for continual observation of soil moisture level. The main disadvantage of this meter is that at lower soil moisture levels, the meter becomes unstable and difficult to operate. Moreover after a long operation time, plant roots could disturb the meter readings [35]. Therefore ongoing maintenance is required around the meter probes.

Darold Wobschall [36] used two capacitor plates to measure the dielectric constant of the soil. The Colpitts LC resonance circuit is used to measure the soil moisture level, when the capacitance increases at the soil electrodes, the frequency of the oscillator shifts. The frequency counter was used to record the frequency shift. The Colpitts oscillator is used, because it is economical, stable and accurate in most situations. A capacitor T network was used to minimise the conductive effect of soil on the frequency shift [36].

A Clapp Oscillator was used to measure the soil moisture content by P. Boyapati and K. Shenai [37]. Two plates are used to measure the dielectric constant of the soil. When the soil moisture increases the capacitance of the probe increases, and this causes to oscillator frequency to decrease. The main aim of this design was to develop a low cost and low power sensor which can be used in a wireless sensor network. This design relies on a microcontroller for calibration and processing of the signals[37]. The main downside of the Clapp oscillator is it is more suitable for use with valves, which have a high input impedance. With transistors, the oscillator will become unstable and unpredictable with varying temperature.

A fringing electric field capacitance based soil moisture sensor was designed by S.Sulaiman and A. Manut [30]. The main objectives of this design were to be small, affordable, able to perfom remote monitoring, durable and easy to deploy in a large scale project [30]. The sensor can be visualized as a parallel plate capacitor, whose electrode opens up to provide a one sided access to the material (soil) under test. The main weakness of this design is the capacitive probe was designed on Printed Circuit Board (PCB) material, and once the PCB is exposed to harsh environments, it starts tarnishing. Therefore its useful life will be very short.

The other possible soil moisture monitoring technique is a bridge circuit (refer to Figure 25). This circuit is easy to build, but the accuracy of the circuit is dependent of resolution of the Analog to Digital Convertor (ADC). The other disadvantage is this design requires good earth signal isolation in order to achieve a reliable analog signal output.

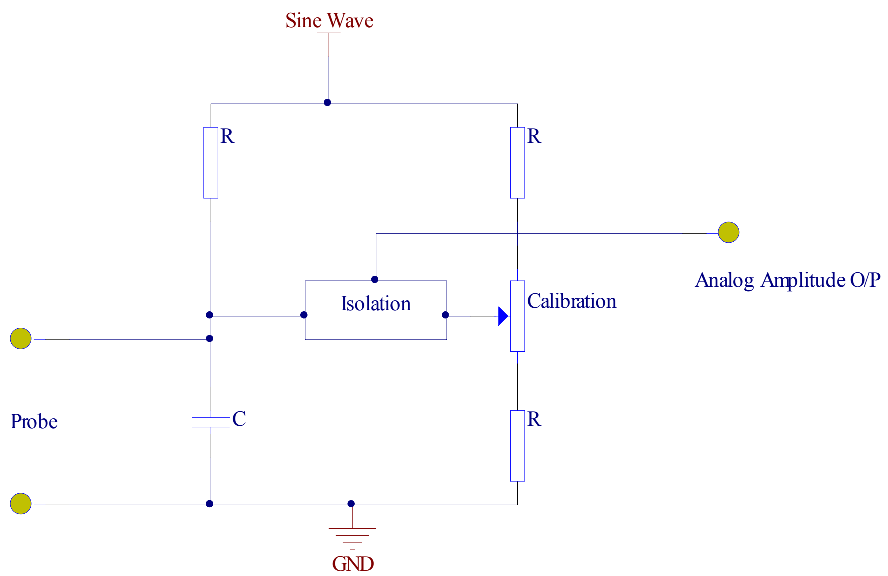


Figure 25: Bridge Circuit

By considering all these recent advances and developments, it was decided to use a capacitive based soil moisture sensor, due to ease of construction, and affordability for a large scale project. The design output is stable and easy to deploy. There has been no research published using a series fed Hartley oscillator in a soil moisture sensor. The series fed Hartley oscillator provides better stability with respect to supply voltage and temperature than a normal Hartley or Colpitts oscillator. Therefore it was decided use a series fed Hartley for soil moisture sensing.

4.3 Environmental Sensors for Micro Climate Weather Station

Most of sensors used in this weather station design are commercially manufactured. These ready made sensors are manufactured under controlled conditions and calibration factors are built into the sensors, or software calibration algorithms are provided with the datasheet. Therefore if possible off- the-shelf parts are used, to reduce the development time and cost. Except for the soil moisture sensor, the sensors used were bought as individual parts and signal conditioning circuit and calibration circuits are designed and assembled in-house.

Temperature Sensor (AD22100): Analog Devices's AD2210 is voltage output temperature sensor with in built signal conditioning. It has a temperature span of 200 °C. The accuracy of the sensor is better than ±2% of full scale. The linearity of the sensor is better than ±1% of full scale. The sensor can operate over a temperature range of -50°C to +150°C. The built in signal conditioning eliminates the need for any trimming, buffering or linearization circuitry. The output temperature coefficient is 22.5mV/°C.

Humidity Sensor (HIH-4030-001): Honeywell's HIH-4030-001 is voltage output humidity sensor with in built signal conditioning. It has near linear voltage output vs %RH (Relative Humidity). The sensor is manufactured with laser trimmed, thermoset polymer capacitive sensing elements. The sensor has a sensing accuracy of ±3.5%RH. This capacitive sensor has a response time of 5 seconds in slow moving air.

Pressure Sensor (MPX2053): Freescale Semiconductor's MP2053 is a highly accurate and linear voltage output sensor. Its output voltage is directly proportional to the applied pressure. The sensor is made out of a single monolithic silicon diaphragm with the strain gauge and a thin film resistor network. The sensor has an operating range of 0 to 50 kPa. It is temperature compensated and calibrated for a range of 0°C to +85°C. It has a differential voltage output of 40 mV over full pressure span.

Sunlight Sensor (NORPS-12): Silonex's NOPRS-12 is a Light Dependent Resistor (LDR). It has an impedance range of 5.4 KΩ to 1 MΩ. The spectral peak response of the LDR is at 550 nm. The operating temperature range is -60°C to +75°C.

Leaf Wetness Sensor (Davis Instruments 6420): Davis's leaf wetness sensor detects the presence of surface moisture. The sensor is an artificial-leaf electrical resistance type. It consists of a sensing grid and low voltage bi-polar excitation circuit. It measures the conductivity across the gold plated grid. It requires a supply voltage of 3V and has an output voltage of 2.5 to 3VDC. This output voltage represents the leaf wetness scale of 0 to 15. The accuracy of the sensor is ±0.5. The sensor has a sensing area of 28 cm^2.

5 Wireless Sensor Network (ZigBee Mesh)

As discussed in the methodology chapter, the ZigBee mesh network was selected to transport the data from each sensor node to the main computer. Non beacon mode is used to transport the data. Data is measured every minute and sent to the coordinator node. The main advantage of the mesh network as mentioned before is that it is self configurable, self healing and expandable. There are two types of devices used in this project: Coordinator and Router nodes.

5.1 Wireless Sensor Network Architecture Applied in Vineyard

Proposed mesh network architecture is shown in Figure 26 below. All the sensors are mounted with router nodes. Each router node contains seven different sensors. According to the customer requirements, data is measured every 1 minute and transferred to the coordinator node, and then it transfers the data to the computer via a Universal Serial Bus (USB) link. The main reason to use this proposed architecture, is to simplify the mesh network, hardware and software requirements. Apart from the end node, only two sets of hardware (coordinator and router) and two sets of generic firmware code (firmware for coordinator and router) are required. The reliability and flexibility of the network is improved by only using router nodes. This system is an ad hoc multi-hop system. Mesh networks are based on the ZigBee protocol, which means each node can be used to send and receive data. Therefore the network consists of multiple redundant communication paths, which can be used in event of node failure. The data will reach its destination reliably via the intermediate nodes (refer to Figure 26) [17].

The downside of this architecture is router node will consume more power than the end node, but at the moment power consumption is not an issue due to use of solar panel battery charger to charge the batteries during the day time.

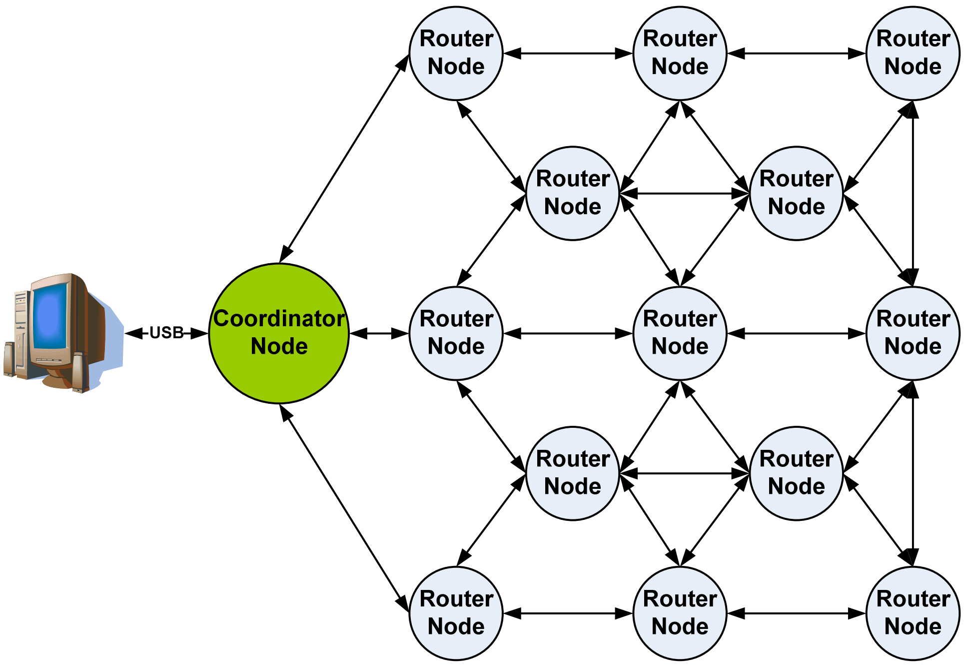


Figure 26: A mesh network topology applied in a vineyard monitoring application [17]

The data transfer between the coordinator node and the computer is performed through the USB port. The coordinator receives data from the router nodes with a node ID followed by sensor ID with sensor data. The end of each string is marked with "#" (refer to Figure 27).

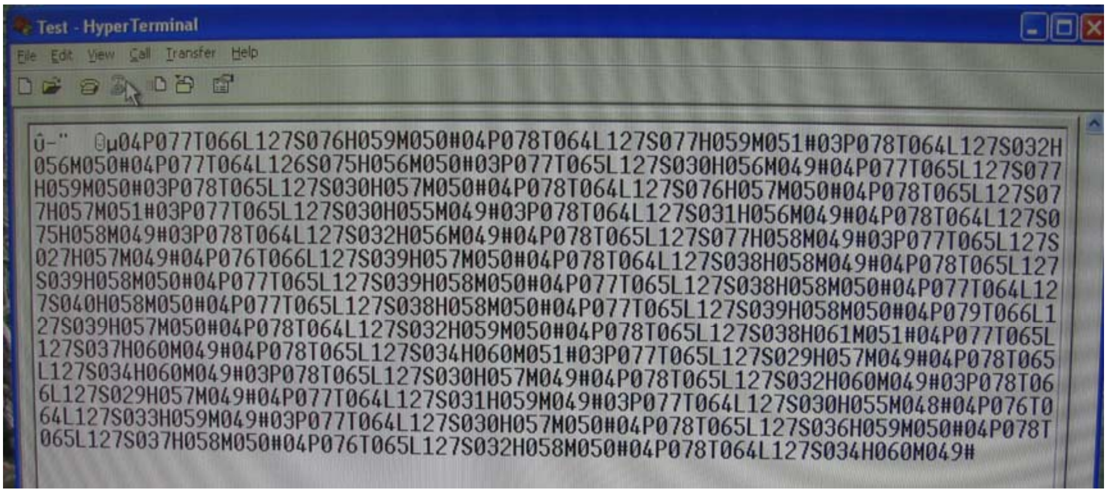


Figure 27: Router Node Data Format

5.2 Hardware Design

The hardware implementation of the router and coordinator node can be separated into two separate designs. The main common component for both designs is the wireless microcontroller module. This module is a standalone module which can be plugged into either router or coordinator nodes. It has a micro strip line PCB antenna and its own regulator module to create correct voltages for the wireless microcontroller CC2430. A USB dongle is used to transfer the data from the coordinator module to the computer.

5.2.1 PCB Antenna

The antenna is a key component for communicating over the maximum distance in a wireless sensor network system. The sole purpose of the antenna is to provide transmission of data electromagnetically in free space. Antennas are divide into single ended and differential antennas. Single ended antennas are commonly called unbalanced, while differential ones are called balanced. In a single ended antenna, the signal is fed at one point which is referenced to ground and the characteristic impedance for these antennas usually 50 Ω. Most RF controllers have differential ports, so a balun is required to transform the balanced signal into an unbalanced signal (refer to Figure 28).

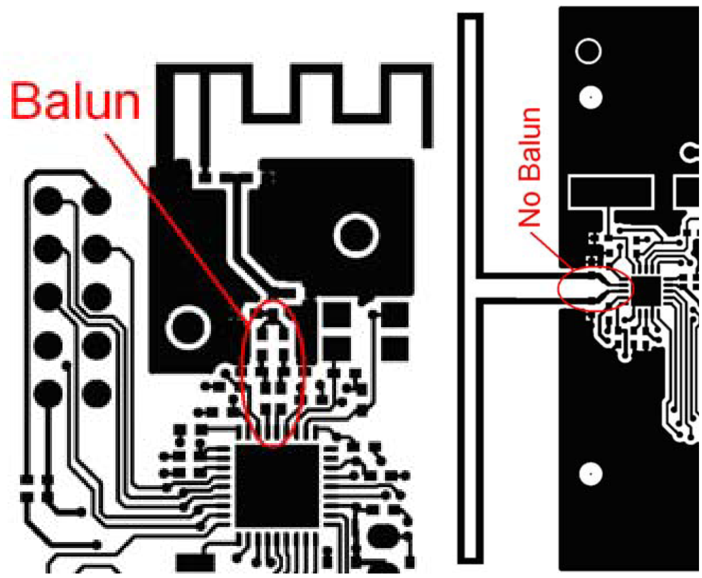


Figure 28: Single Ended and Differential Antenna [38]

It is important to select the appropriate antenna for the hardware design, in order to save money and increase the operating range. There are three main solutions, which can be used at 2.4GHz range with the CC2430 microcontroller. The three options are the PCB antenna, Chip antenna and Whip antenna [38] (refer to Figure 29).

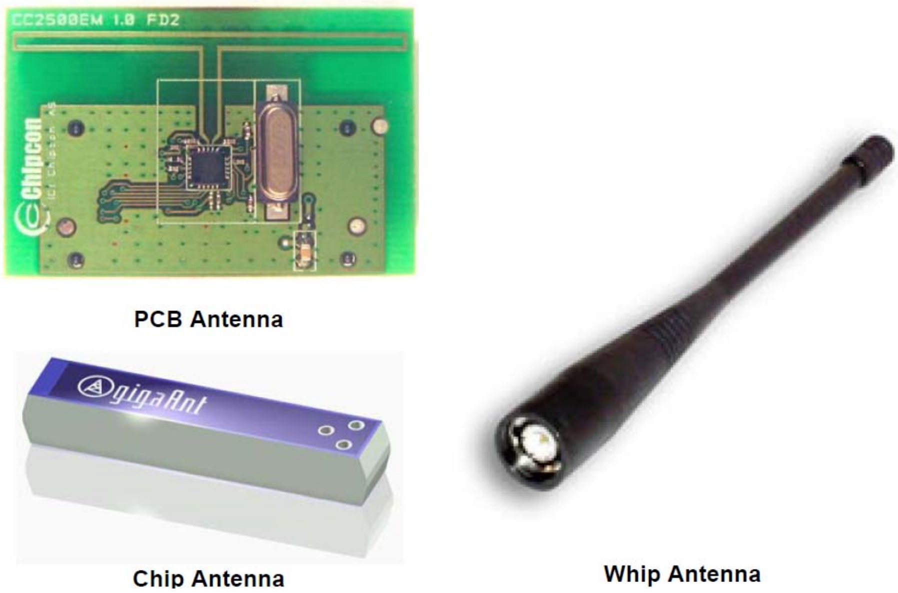


Figure 29: Different Antenna Solutions [38]

The chip antenna is small in size, and development time of the hardware is short, but the downside is these antennas have medium range performance and medium cost. The whip antenna has a higher cost compared to the chip antenna, but it has a very good performance range. The other major issue with the whip antenna is that it is usually difficult to fit into many applications. Finally the PCB antenna has very low cost, good performance, smaller size at high frequencies and the standard design antennas widely available are not patent protected [38]. Therefore it was decided to use the PCB antenna, in order to reduce the cost and increase the operating range.

Three PCB antenna options were considered: 2.4GHz TI small size antenna, 2.4 GHz inverted "F" antenna and Folded Dipole antenna. It was decided to use the Folded Dipole antenna (refer to Figure 30). This is because it has a simple differential interface to the CC2430 microcontroller. The simple design does not require complicated drawings and because of the differential interface the design does not require a balun. The other two designs are single ended and therefore they require a balun and more components. More importantly, if the Folded Dipole antenna is matched properly, it has a longer range than the other two.

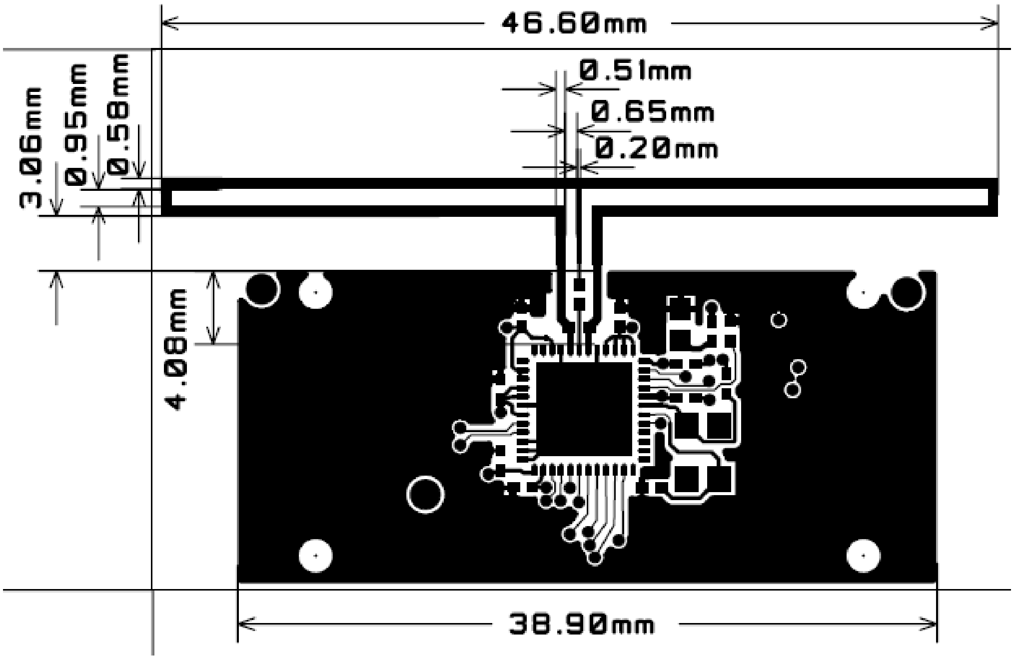


Figure 30: Folded Dipole Antenna Reference Design [39]

The optimum termination impedance is a trade off between optimum source impedance for the internal low noise amplifier and optimum load for the internal power amplifier. The CC2430 microcontroller has a TX/RX switch pin. When the radio is receiving data this pin provides 0 V for the low noise amplifier, and when it is transmitting it provides a 1.8 V supply voltage to the power amplifier. This pin must be isolated for RF signals by using a shunt capacitor or a series inductor [39]. In typical short range device applications, this antenna is suitable because it radiates equally in all directions. In other words, this antenna is omni directional.

The high impedance makes the folded dipole antenna an attractive choice because it is easier to match to the optimum impedance for CC24xx devices. The theoretical impedance is 292 Ω for a half wavelength folded dipole. The shunt inductor provides the inductive part of the optimum load impedance and reduces the real part. The folded dipole antenna is a metal loop, which loops between the RF pins and provides DC contact. The mid point of the antenna is a virtual ground. Therefore connection can be made to the RX/TX switch pin without any interference to the performance of the antenna. The folded dipole has a resonant structure and hence it is less sensitive to component variations and has low losses. The radiation pattern is omni directional in the plane normal to the antenna [39].

5.2.2 AUT Wireless Microcontroller Module

The basic microcontroller board module is designed to interface with the sensor and the computer dongle. The ZigBee based CC2430 wireless microcontroller is used in this module. This microcontroller has an on chip 2.4GHz IEEE 802.15.4 compliant RF transceiver, a high performance and low power 8051 microcontroller core, 128KB in-system programmable flash, 8KB Random Access Memory (RAM), two powerful UARTs, 21 general I/O pins, an ADC with up to eight inputs and configurable resolution, wide supply voltage range (2.0 V – 3.6 V), low current consumption (RX: 27 mA, TX: 27 mA, when the microcontroller is running at 32 MHz), 0.5μA current consumption in power down mode, where external interrupts or the Real Time Clock (RTC) can wake up the system, 0.3 μA current consumption in power-down mode, where external interrupts can wake up the system, battery monitor and temperature sensor and other useful features. Figure 31 below shows the main controller unit, which has the folded dipole PCB antenna, on board power supply and with all the I/O ports connected to two header connectors.

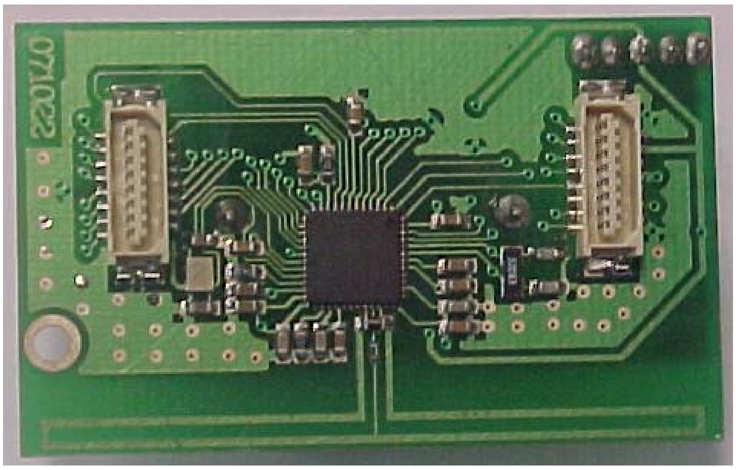


Figure 31: CC2430 Microcontroller Module

The on board power supply consists of 3 V and 1.8 V ultra low voltage drop regulators. This power supply can accommodate either an external power supply via header pins or a 3 V cell battery. For the power source selection, a single pole double throw (SPDT) power switch is used. Two crystals are used in this module. The 32 MHz crystal is used to run the system at full speed and a 32.768 KHZ crystal is used to run the system in sleep modes and to run the wireless transceiver. The microcontroller can be programmed or debugged via the System on Chip (SOC) header (refer to Figure 32). The powerful SOC debug interface provides a two-wire interface to an on-chip debug module. The debug interface allows programming of the on-chip flash and it provides access to memory and register contents and debugging features such as breakpoints, single-stepping and register modification.

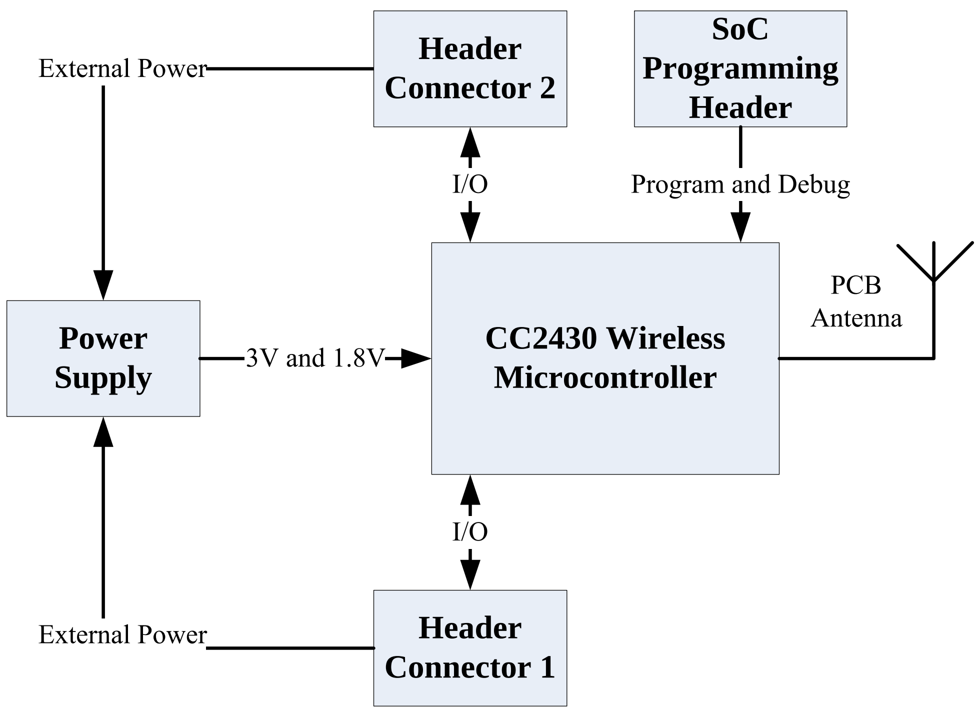


Figure 32: Block Diagram of Wireless Microcontroller Module

The main aim of this modular design is to utilise this microcontroller module in different applications. In this research, the same module is used in the coordinator USB daughter board and the router sensor daughter board (refer to section 5.2.3 and 5.2.4). The wireless microcontroller module was previously developed. It has been used in other projects such as "*Spike: A Six Legged Cube Style Robot*" [40], "*Power Characterisation of a ZigBee Wireless Network in a Real Time Monitoring Application*" [41] and some internal student projects within the School of Engineering, and has been found to be very suitable. This module could also be successfully used as a teaching platform.

5.2.3 Sensor Module (Router Node)

The micro climate weather station needs to monitor several different environmental parameters. These parameters are monitored using the sensor board module. The sensors are integrated into one daughter board. The wireless microcontroller module is plugged into the daughter board and the sensor readings are obtained via the ADC port and UART port. The sensor module comprises seven different environmental sensors namely pressure, leaf wetness, sunlight, humidity, air temperature, soil moisture and soil temperature (refer to Figure 33).

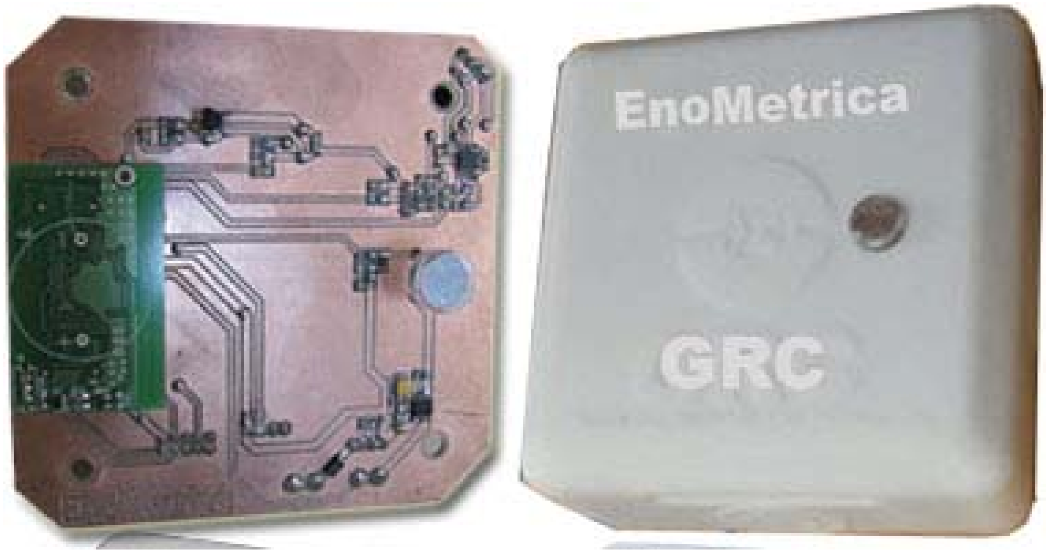


Figure 33: Micro Climate Weather Station

The sensor module can be divided into two main parts, the wireless microcontroller module and sensor board (refer to Figure 34). This module is a router node in the ZigBee mesh.

To measure the atmospheric pressure, the MPX2053 sensor is used. This sensor has a differential output, and therefore INA118U instrumentational amplifier is used to change the output signal to a single ended voltage and to amplify the signal to the 0 - 3 V range.

To measure the sunlight, a light dependent resistor (LDR) is used with a voltage divider. The output data is scaled from 0-100000 lux into 0 – 3 V.

The HIH-4030-001 relative humidity sensor's output voltage range is 0 – 5 V. Hence this range is not suitable for the CC2430's ADC input. A resistor divider is used to scale down the voltage.

To measure the temperature, the AD22100KTZ active temperature sensor is used. A resistor divider is used to scale down the voltage to suitable level for the ADC input.

A Davis commercial leaf wetness sensor is used to measure the leaf wetness. This has a dynamic range of 2.5 – 3 V, for a leaf wetness of 0 -15.

The Soil moisture and temperature sensors are connected to the CC2430 through UART port.

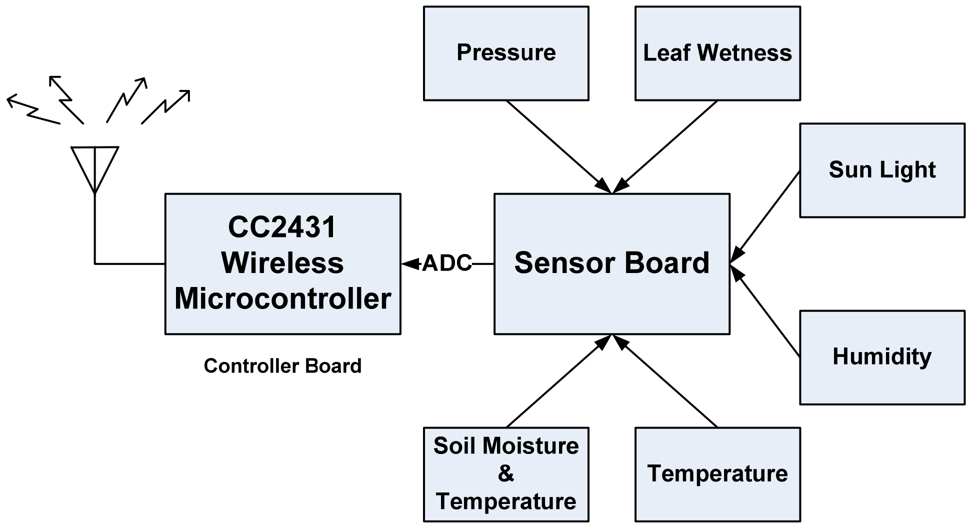


Figure 34: Block Diagram of the Sensor Module

The main purpose of this sensor module is to collect data and transmit the data to the main coordinator node. At present the microcontroller collects data very minute and transmits the data to the coordinator. All the data is stored into a string and transmitted with node ID. The second purpose of this router unit is to record each neighbouring sensor's IEEE ID in a look up table and route its data to the coordinator by the fastest route. In case of an adjacent node failure, the node will go through the look up table and reroute data through other neighbouring sensor nodes.

5.2.4 USB Coordinator Dongle Module

The coordinator is used to collect information from the network and transfer the data into the computer via a USB port. This board is powered through the computer USB power supply. Once data is received from the network, sensor data is transferred to the RS232 to USB converter. The converter sends the RS232 data to the computer via the USB port (refer to Figure 35).

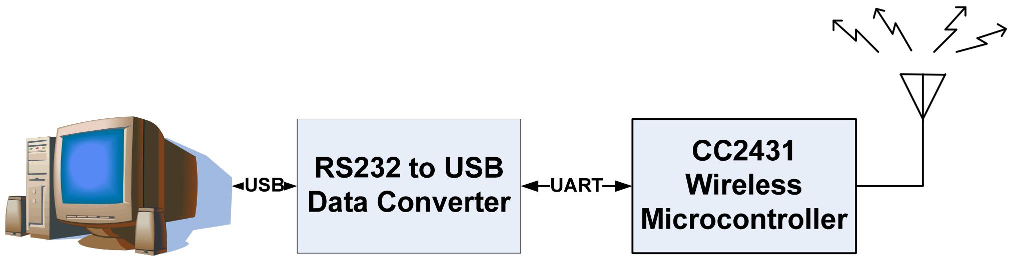


Figure 35: Coordinator Node Block Diagram

Every time a new node is connected to the network, the coordinator will identify the node and issue the new node with an IEEE address. During the communication between these nodes, the coordinator identifies each data packet using the node IEEE address.

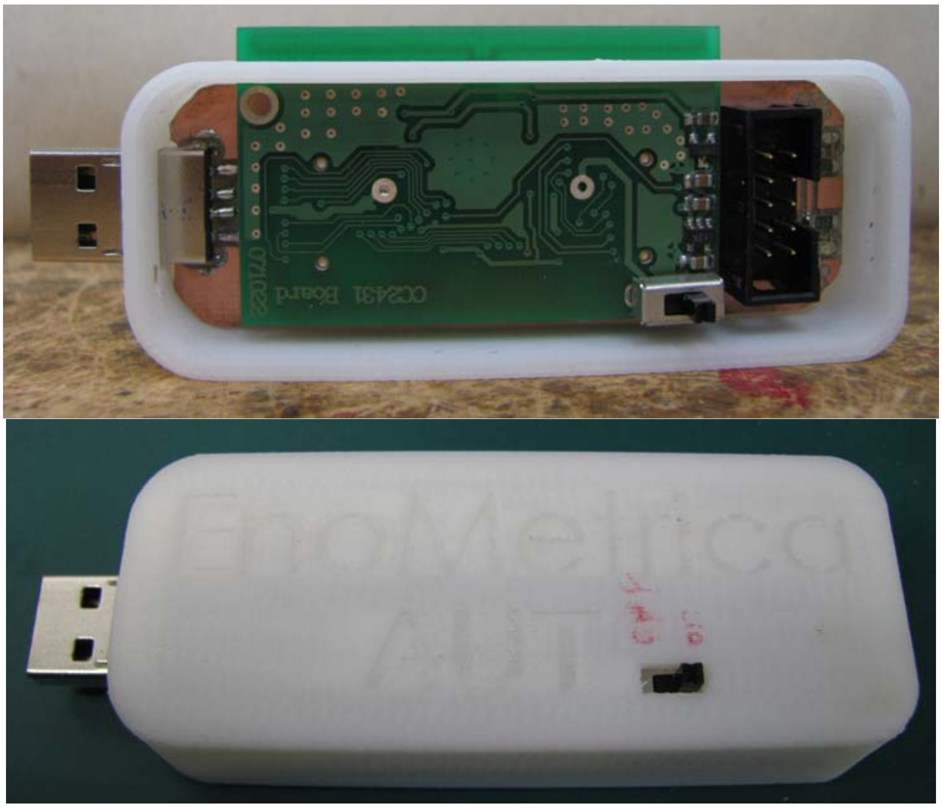


Figure 36: Coordinator USB Dongle

The FT232R USB UART integrated circuit (IC) device is used convert UART data from the CC2430 wireless microcontroller device. This IC provides the link between the computer and the coordinator node via USB port. USB interface is required in this application as most new computers do not have any RS232 ports.

5.3 Enclosure Design and Fabrication

The Solidworks 3D software package was used to design the router sensor node and coordinator node casings (refer to Figure 37). Solidworks is a powerful 3D graphics design software package, which can be used to design and visualise the 3D object.

Once a 3D object is designed on Solidworks, this design can be printed on a 3D printer. This process is called rapid prototyping. This technology allows for the creation of complex 3D prototypes in a very short period of time. This process helps to test the product concept for aesthetics, ergonomics, or engineering functionality. This process allows ideas to be trialled and tested before going into production. It also allows making faster iterations of the product development process before finalising the design. The AUT Rapid Prototyping Lab can produce parts in a variety of materials including plastic, plaster and aluminium

The sensor node enclosure design is specially made to provide ventilation for the circuitry, but at same time stop the water getting inside. There are four ventilation openings around the enclosure. These openings have a specially curved inside trap, which traps the water and removes the water to the outside (refer to Figure 37). There are four, 4 x AA battery holders fitted inside the enclosure. These battery holders are placed around the enclosure. All the connectors are placed in the middle of the PCB, so in the enclosure all data and power cables can be accessed through the middle of the enclosure to the mounting pole. The enclosure can be mounted onto standard 32mm polyvinyl chloride (PVC) water pipe. There are four mounting studs inside the enclosure to mount the PCB. There is circular opening on the top, so the light sensor can be installed through the opening (refer to Figure 37).

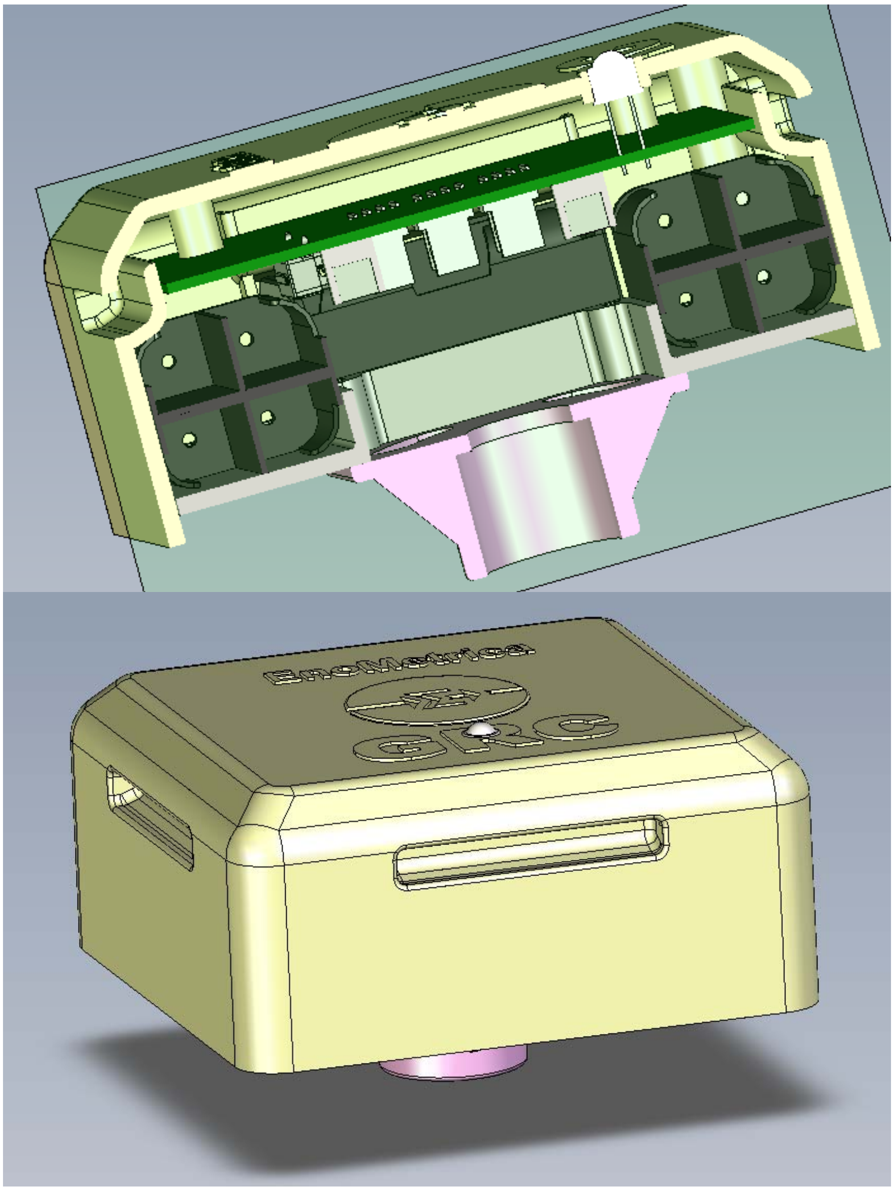


Figure 37: Solidwoks 3D Drawings of the Sensor Node

The plastic 3D printer used in AUT University is a Dimension 768 SST (refer to Figure 38), which uses Fused Deposition Modelling (FDM) technology to produce parts in Acrylonitrile Butadiene Styrene (ABS) plastic, with a resolution of 0.254mm per layer. The specifications of the machine are as follows:

- Material: White ABS
- Maximum size 203 x 203 x 305 mm
- Layer Thickness: 0.254 mm or 0.33 m

Figure 38: Dimension 768 SST 3D Printer

5.4 WSN Embedded Software

There are two embedded programmes for the wireless nodes. The coordinator node and router node have different application layer firmware code. The aim of the router node is to extract the data from the sensors and packet the data for transmission. The coordinator node receives the data and sends the data to the computer for further processing. Both nodes have same IEEE 802.15.4 PHY and MAC stack, ZigBee Stack, and then finally separate application layer (refer to Figure 39).

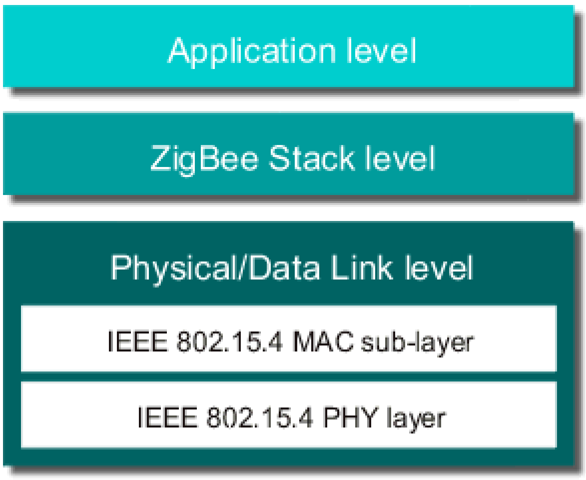


Figure 39: Basic Architecture of ZigBee

The Physical data link layers handle lower level operations, such as addressing and message transmission, and reception and data handling from sensors. The physical layer controls all the basic hardware level operations.

The ZigBee stack layer provides ZigBee functionality, and links the application layer and the physical layer. This layer consists of network structure, routing and security (encryption, key management and authentication).

The application layer contains the application code that runs on the node. The application layer defines the functionality of the node. Basically an application converts input signals into digital data and output the data to the network or to the computer.

In the micro climate weather station, the application layer on the router extract the data from the sensors by using the microcontroller's ADC and stores the data into a string. The ADC on the micro needs to be initialised and the ADC port number needs to be defined. The code snippet shown below defines the ADC port and the resolution of the ADC. The ADC function is part of the Real Time Operating System (RTOS).

```
Message = HalAdcRead (1, HAL_ADC_RESOLUTION_8);
```

The physical layer takes care of all the lower level setup in control registers. In the application layer, the ADC read function returns the ADC data for a given resolution and port number.

In order to read the data from the soil moisture sensor, UART parameters needs to be initialised. The code snippet shown below is used to initialise the UART.

```
HalUARTInit();
halUARTCfg_t config;

config.baudRate = HAL_UART_BR_38400; // or 115200
config.flowControl = FALSE;
```

```
config.idleTimeout = 50;

config.rx.maxBufSize = 50;
config.flowControlThreshold = 0;
config.tx.maxBufSize = 50;

config.intEnable = TRUE;
config.callBackFunc = NULL;
HalUARTOpen(HAL_UART_PORT_0, &config);
```

Once the UART port is initialised and opened, the data can be read from the soil moisture sensor. Once all the analogue and digital data is collected, data is stored into a one main string. Then this string is transmitted to the coordinator node.

In the coordinator node, the application layer receives the data from the router nodes. Incoming data packets can be received using the ZigBee function below.

```
MSGpkt =(afIncomingMSGPacket_t*)osal_msg_receive(GenericApp_TaskID );
```

Once data is received, it can be copied to the serial string by using the ZigBee memory copy function.

```
osal_memcpy(Serial_Data,pkt->cmd.Data,osal_strlen((char*)pkt->cmd.Data));
```

Once all the serial data is received, the serial port write function is used to transfer the data to the computer (refer to code snippet below).

```
HalUARTWrite(HAL_UART_PORT_0, buf, osal_strlen((char*)buf));
```

6 Soil Moisture Sensor Design

The main aim of the soil moisture sensor is to optimise the water usage of the wine industry in New Zealand and Chile. By maintaining the optimum water level for grapevines, the grape harvest can be improved and water usage can be reduced. The sensor developed in this research will measure the volumetric water content (VWC) at three different depths: 5m, 3m and at surface level. Measuring the VWC at different depths gives a better understanding of the VWC up to the grapevine root levels. To understand the VWC at the micro-level, sensors are to be installed in a rectangular pattern at 100m intervals in the vineyard. A capacitance based, fast reacting soil sensor method is used in this research.

6.1 Soil Moisture Sensor Principle

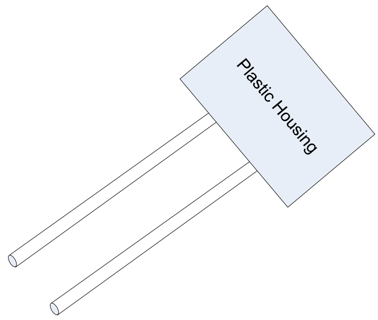


Figure 40: Capacitive Probe

$$C_s = \varepsilon_r C_0 \tag{5}$$

Where:
C_0 is the capacitance in air
C_s is the capacitance in soil
ε_r is the relative permittivity of the soil

The basic principle of operation is to make the capacitive probe part of a series fed Hartley oscillator tank capacitor and to measure the change in oscillator frequency caused by introducing water. The dielectric constant of soil mineralogical materials varies from 2 to 14, and water has a dielectric constant of approximately 80 [42]. Therefore the dielectric constant of soil is a reasonable indicator of the VWC of soil. Adding water to the soil changes the dielectric constant, resulting in an increase in capacitance of the soil and this causes a decrease in the frequency of the oscillator (refer to formula 6).

$$F = \frac{1}{2\pi\sqrt{LC}} \tag{6}$$

The operating frequency of the oscillator is one of the critical factors which needs to be considered before designing the oscillator. The complex permittivity of the soil (ε) can be defined as:

$$\varepsilon = \varepsilon' + j\varepsilon'' \tag{7}$$

The real part (ε') and the imaginary part (ε") respectively represent the dielectric permittivity and the conductivity of the soil.

Equation 7 can be written as:

$$\varepsilon = k\varepsilon_0 - \frac{j\sigma}{\omega} \tag{8}$$

where *k* is the real part of the dielectric constant, ε_0 is the permittivity of free space (8.85×10^{-12} F/m), σ represents the conductivity of soil (mho/m), and ω is the angular frequency (rad/s) at which the measurement is made [43]. It has been found that for frequencies higher than 10MHz, the imaginary part of the complex permittivity has an insignificant effect [36, 37, 44].

The series fed Hartley oscillator is designed to operate at 18.75MHz when the surrounding soil is fully dry. The sensor has a full frequency range of 2.35MHz variance from fully dry to 100% wet. Therefore the effective range of the sensor is 18.75MHz down to 16.4MHz as the soil moisture content changes from 0% to 100%.

6.2 Clapp Oscillator Design

Initially a Clapp oscillator was selected to measure the capacitance of the soil. The main reason for the selection was its simple design, requiring fewer components. The Clapp oscillator circuit was designed and built (refer to Figure 41 and Figure 42).

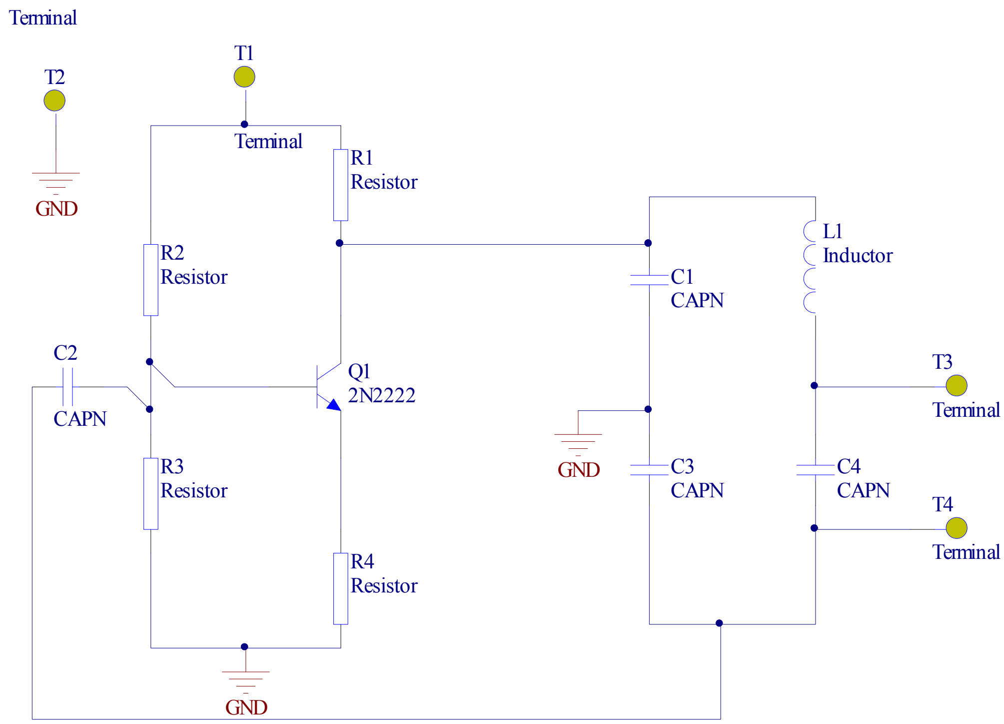


Figure 41: Clapp Oscillator Schematics

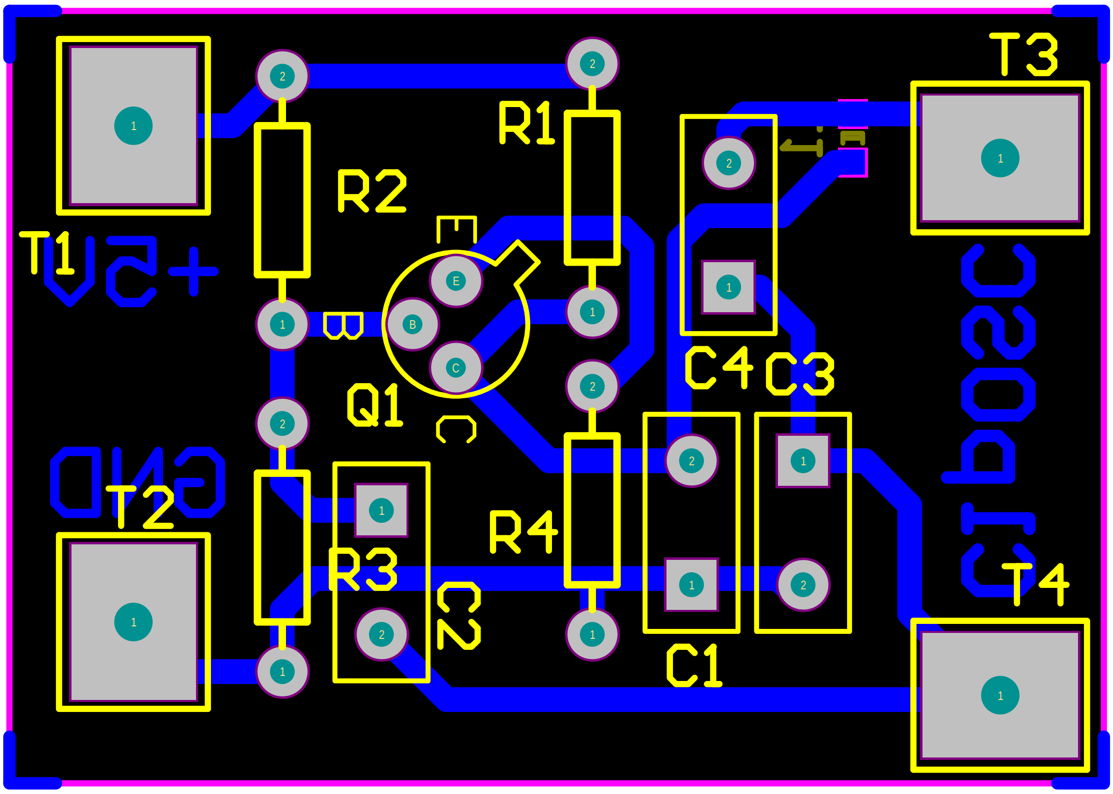


Figure 42: Clapp Oscillator PCB Design

The circuit was tested on different soil samples and it was found the oscillator had considerable drift with temperature. Moreover the oscillator is unstable, and sometimes it would not oscillate. After some investigation, it was found the Clapp oscillator was designed for use with valves, which have high impedances. It is unsuitable for use with BJTs.

Therefore it was decided to use a series fed Hartley oscillator. The circuit enables a good impedance match inside the feedback loop over a range of frequencies which makes its behavior more predictable than the Clapp oscillator.

The frequency stability of a BJT oscillator is affected by the characteristics of the transistor, the stability of the supply voltage, loading at the input and output, and the effect of temperature on all the component characteristics.

6.3 Soil Moisture Sensor System Design

The soil moisture sensor design is shown in Figure 43 [45]. The main delicate part of the design is series fed Hartley Oscillator. The oscillator generates the varying frequency, depending on the soil moisture level across the probes. The manual initial calibration is performed varying the coil loading. The oscillator output frequency feeds into the frequency down convertor.

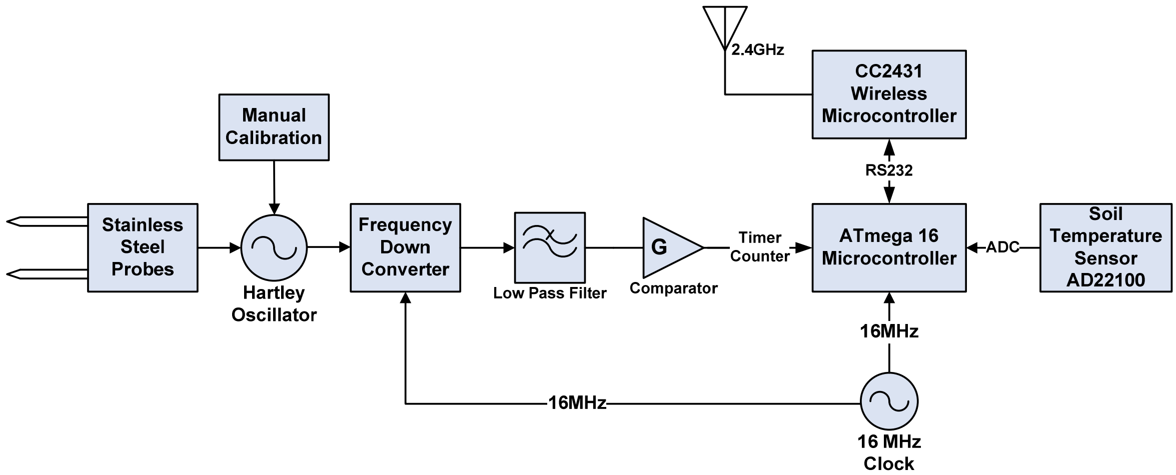


Figure 43: Soil Moisture Sensor Block Diagram [45]

The series fed Hartley oscillator provides better stability with respect to supply voltage than a normal Hartley or Colpitts oscillator. However it was still essential to provide a power supply which is stable to better than 0.5% overall possible temperature and load variations.

It is difficult to quantify the overall outcome of the effects of temperature on all the components. Therefore, it was decided to use components with known and reproducible properties (such as temperature coefficient of capacitance) and compensate with suitable circuitry. The circuit below (refer to Figure 44) was stable to better than 0.04% over a temperature range of 90°C. The Q5 transistor provides active biasing for the Q4 transistor for temperature compensation. Due to the temperature compensation the Q4 transistor always operates in the hard saturation region. Therefore the oscillator is not operating in a linear region. Thus the normal linear analysis does not apply for the oscillation characteristic. Temperature stability is one of the important characteristics of this design, in order to achieve repeatable and reliable readings in varying environmental temperatures. Most other soil moisture sensor research designs do not incorporate temperature compensation and stability in their hardware design.

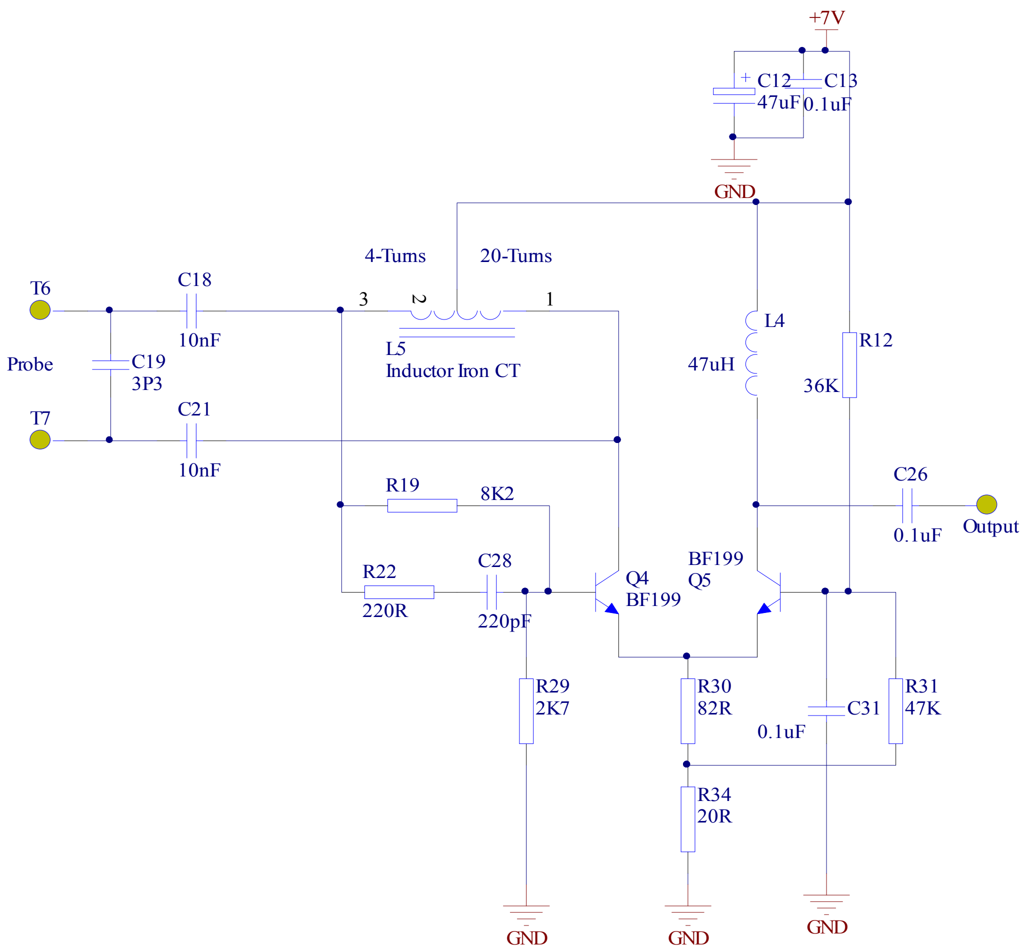


Figure 44: Series Fed Hartley Oscillator

This circuit (refer to Figure 44) above uses Q5 to offset any drift in the oscillator circuit of Q4. To minimise the effect of loading at the output, a buffer stage was required.

The microprocessor was used to measure the oscillator frequency. A frequency down convertor was used to reduce the 16.4 to 18.75 MHz oscillator output frequency to a lower frequency that the microcontroller could measure. For simplicity and due space constraints, a basic down convertor was used (refer to Figure 45).

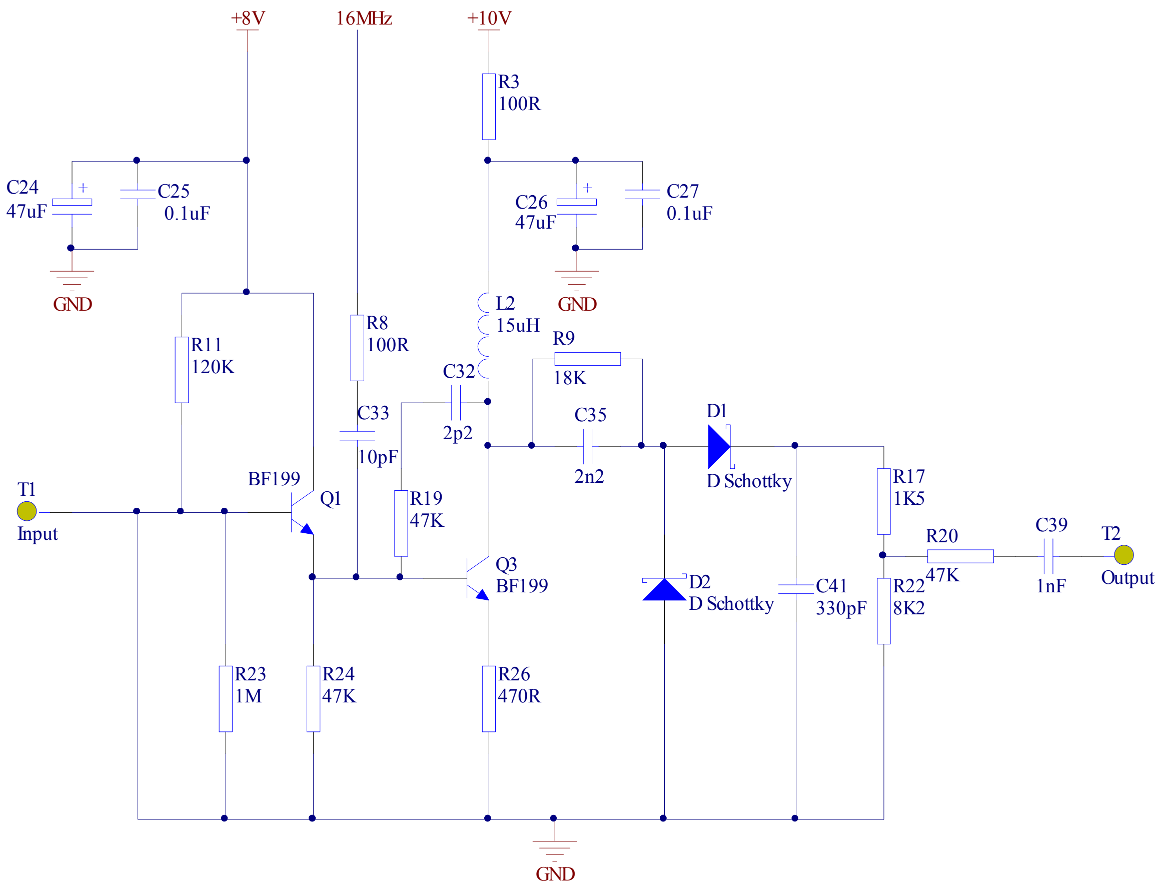


Figure 45: Down Convertor

The down convertor multiplies the16MHz reference frequency from the crystal with the frequency from the oscillator. D1 and D2 form an unbalanced diode mixer, down convertor. This down convertor uses the non linearity of the diodes to multiply two signals together. Once the two frequencies are multiplied together the outcome is two frequency components, the sum of the two frequencies and the difference of the two frequencies (refer to equation 11).

The input signals are sinusoidal waves represent as:

$$v_i(t) = A_i \sin 2\pi f_i t$$

9

Where:

Each A is amplitude

Each ***f*** is a frequency

t is time

Using trigonometric identity:

$$\sin(A) \times \sin(B) \equiv \frac{1}{2}\left[\cos(A - B) - \cos(A + B)\right]$$

10

By applying trigonometric identity equation 10 to equation 9:

$$v_1(t)v_2(t) = \frac{A_1 A_2}{2}\left[\cos 2\pi\left(f_1 - f_2\right)t - \cos 2\pi\left(f_1 + f_2\right)t\right]$$

11

Where the sum $(f_1 + f_2)$ and difference $(f_1 - f_2)$ frequencies appears.

A low pass filter is used remove the higher frequency component $(f_1 + f_2)$ and let the lower frequency components $(f_1 - f_2)$ through to the comparator. The input to the comparator has a frequency in the range 400 kHz to 2.35 MHz. The high speed TLV3502 comparator is triggered by the zero crossings of the sine wave and produces a square wave output signal (refer to circuit on Figure 46). The square wave is fed into the timer counter input of the ATmega16 microcontroller.

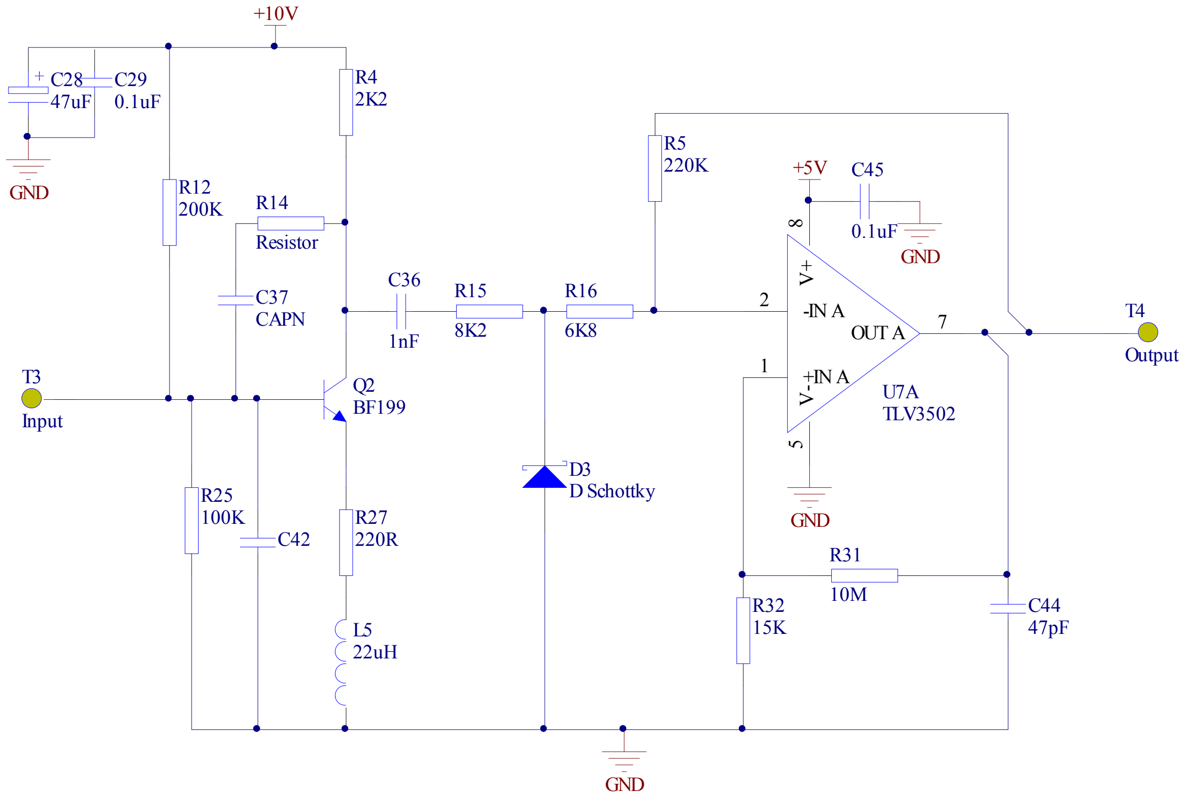


Figure 46: Low Pass Filter and Comparator

The microcontroller counts the pulses from the comparator and converts the count value into the soil moisture content. The microcontroller timer counter is used to count the frequency. At the same time the microcontroller reads the temperature data from the AD2210 temperature sensor. Then both soil moisture and temperature readings are sent to the wireless microcontroller via the UART port (refer to Figure 47).

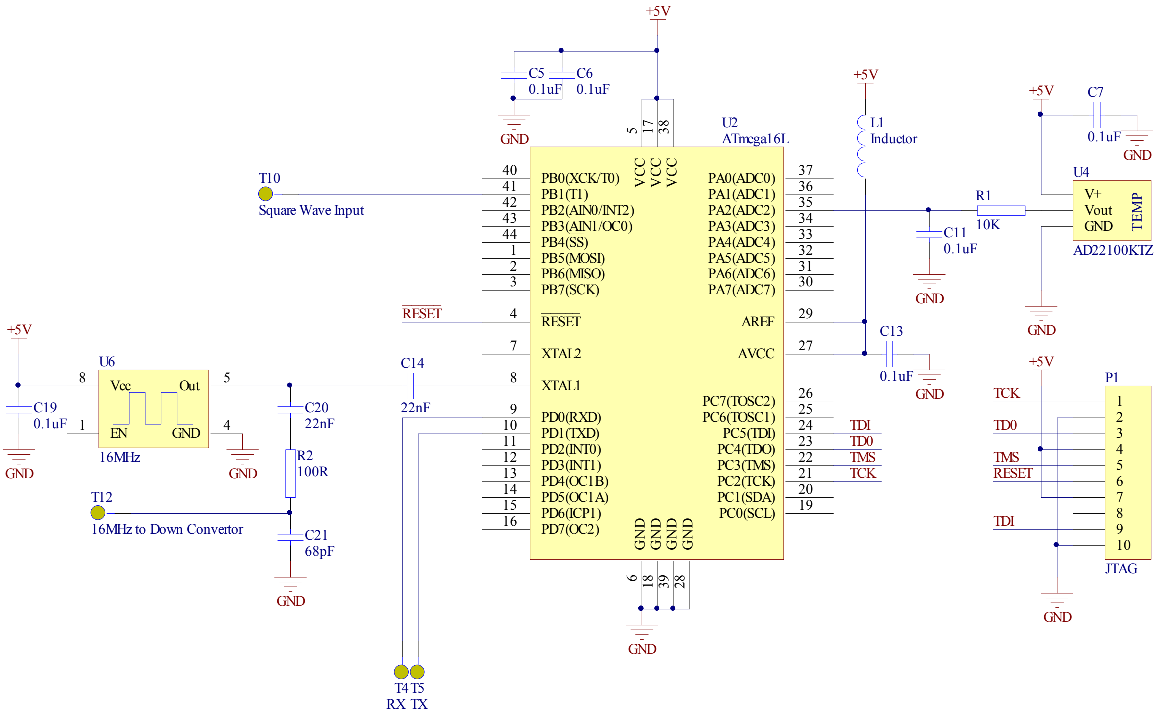


Figure 47: Microcontroller and Temperature Sensor

The basic idea of this design is to bury the soil moisture sensor under ground and transmit the data to the wireless router node via the UART link. The main advantage of the UART link is it is less susceptible to environmental noise and other outside disturbances.

6.4 PCB Design

There were major challenges in the hardware implementation, which had to be considered in final design. The major challenges were that the unit needs to be affordable for large scale application, and needs to have a water tight casing.

The Altium circuit design software package was used to design the soil moisture sensor hardware. Two versions were produced. The first version was unsuccessful due to noise issues. Version two was designed with a new PCB layout to minimise the noise issues.

6.4.1 PCB Design Version One

The first version of the soil moisture sensor was designed (refer to Figure 48). During this design process, RF noise was not taken into consideration. Therefore star grounding was not used. During the testing it was found the output signal from the comparator was hard to trigger due to severe jitter problems. The jitter was introduced from the down convertor, due to RF noise from the oscillator. Therefore it was decided to design a new PCB with star grounding and proper power and signal isolation.

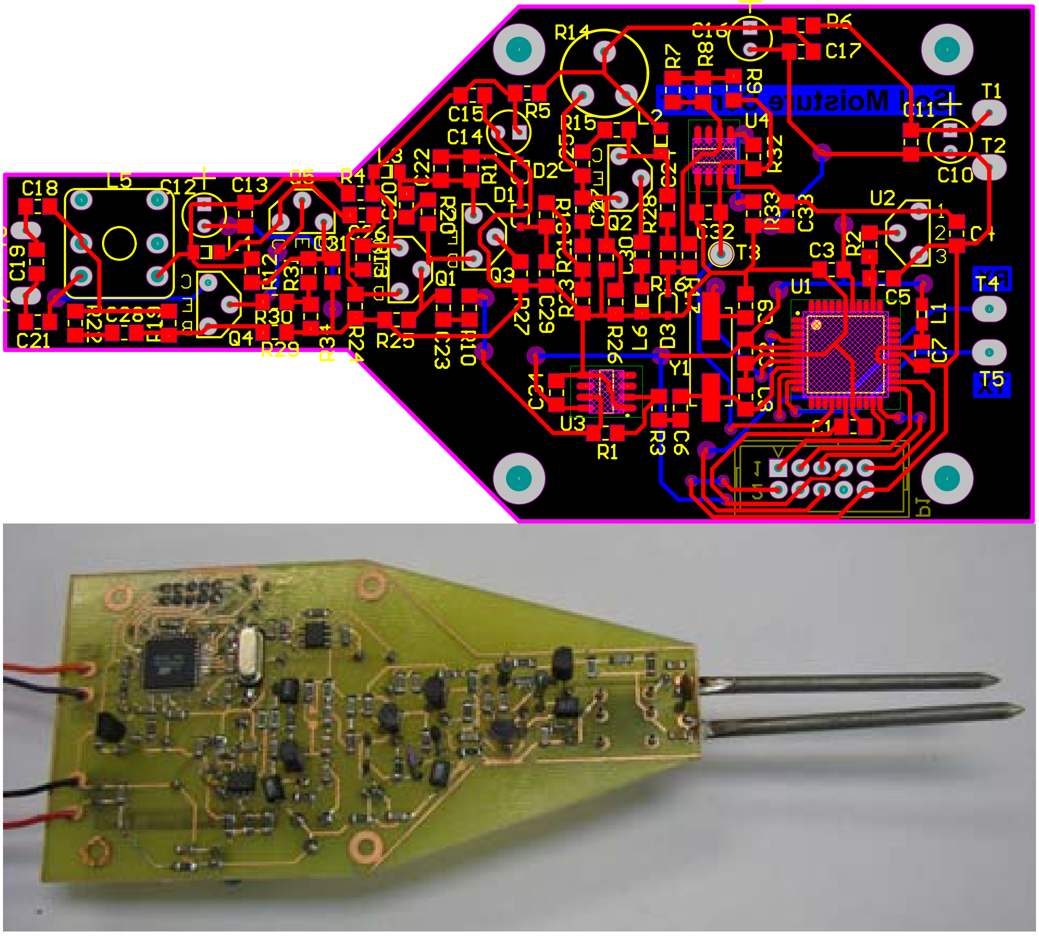


Figure 48: Initial Soil Moisture Sensor Design

In the first design, the reference clock to the down convertor was fed through a high speed comparator, which obtained its input signal from the microcontroller crystal. High speed comparators are normally expensive and require more external components. Therefore it was decided to remove the comparator reference clock circuit, and to use a 16MHz clock IC. The 16MHz clock IC does not require any external components, and the signal output from IC can be fed straight into the microcontroller and down convertor.

The initial enclosure design for this version was an ABS printed casing. Due to the 3D printing and special design, the final cost of the product increased. Therefore it was decided to use a simpler and more robust case for the PCB version two.

6.4.2 PCB Design Version Two

The second PCB was designed with careful planning for RF noise, ground, power supply design, enclosure design and some improvement of the down convertor reference clock circuit (refer to Figure 49).

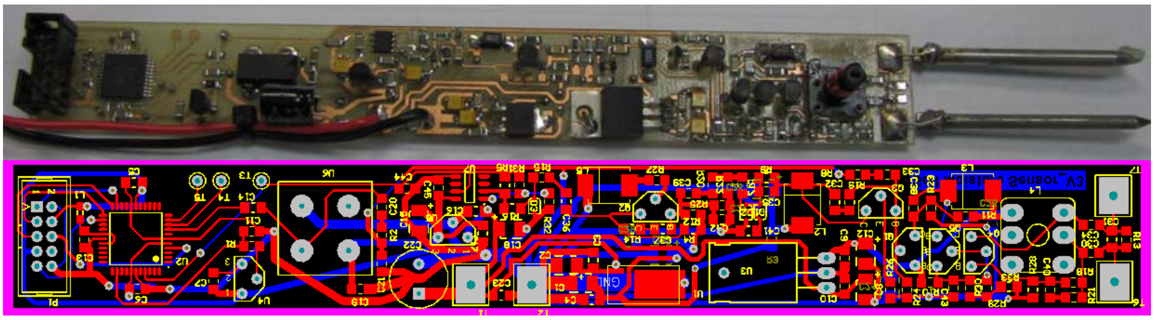


Figure 49: Soil Moisture Sensor

In order to optimise the performance, star grounding is used in this design (refer to Figure 50). The whole design is separated into six main parts: oscillator, down convertor, filter, comparator, power supply regulators and microcontroller. Each part has it own ground track which connects to the one point in the circuit. This point is normally the entry ground point of the circuit. This point is normally called the start point. The main purpose of the star point is to ensure that noise generated by each sector of the circuit will not affect the rest of the circuit. Each sector ground goes to the star point via its own ground path, without causing major interference to the rest of the circuits. In the power system there are three fixed voltage regulators: +5V, +8V and +10V. Each voltage regulator has its own ground track and power track.

Therefore the power inlet pad of the circuit is another star point. Any input voltage fluctuation at any voltage regulator will not affect the other regulators. There is a tank capacitor to further reduce voltage fluctuations.

The main purpose of the three different voltages in the same circuit is to improve the stability of the analogue circuitry. Generally in RF design, an ascending voltage is used from the input point to minimise noise issues and improve the stability of the system. In this design, the oscillator is operating at +8V, the down convertor is working at +9V (a series resistor is used to reduce the voltage), and +10V is used in filter circuit. The comparator and microcontroller are operating at +5V. Hence the comparator produces an output square wave with an amplitude of 5V compatible with the microcontroller inputs.

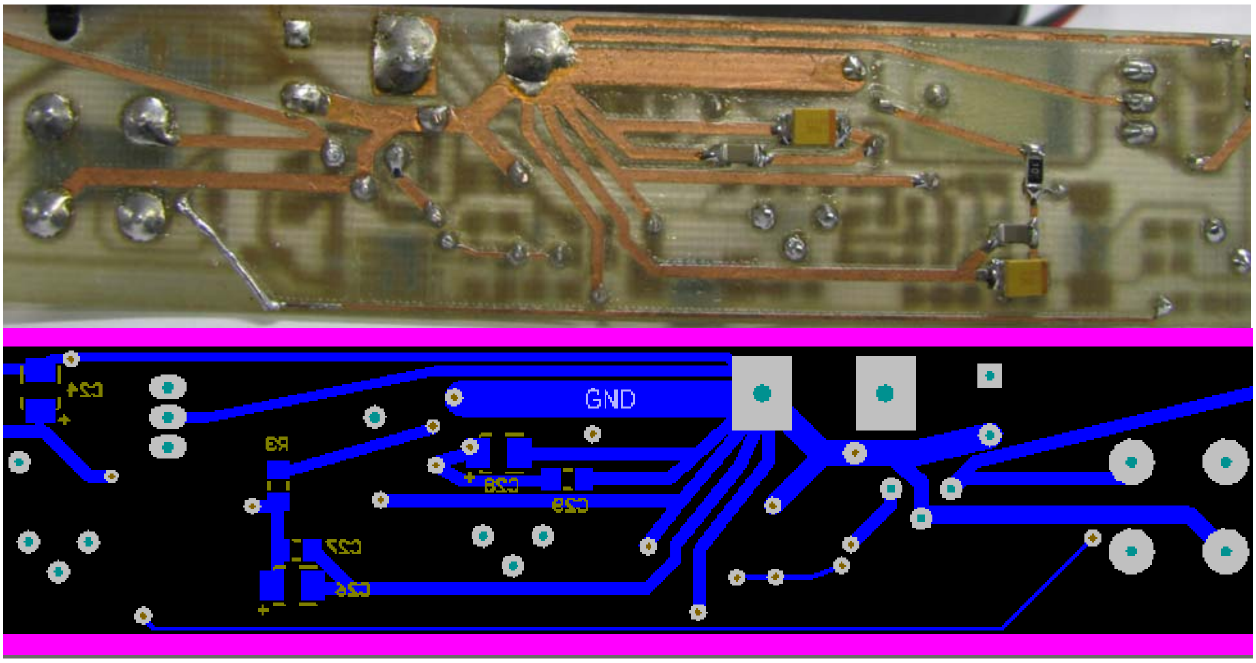


Figure 50: Star Grounding

Heat shrinks were placed over the two probes to protect the probes from soil minerals and helps to make the enclosure water thigh.

6.5 Enclosure Design and Fabrication

Enclosure design for the soil moisture sensor is critical, due to its underground moist environment. The enclosure needs to be cheap, durable water proof and easy to mass produce.

This simple case is designed out of 32mm Polyvinyl Chloride (PVC) water pipe. The printed circuit board's length is 195mm and its width is 26mm. The PCB fits inside the pipe. All the tall components are placed in the centre of the PCB to optimise the height constraint. The other main advantage of using PVC water pipe is it is stabilised to ultra violet (UV) radiation, and therefore it can be used in surface soil moisture measurements without any deterioration to the case from sun light (refer to Figure 51).

Figure 51: Soil Moisture Sensor Enclosure

The end caps for the PVC pipe were specially designed to hold the stainless steel probes and pass the power and data cables through. Both front and end caps have same design. The difference is the utilisation of the cap. The end cap has two un-pierced holes (refer to Figure 52), which are lined up for the stainless steel probes. If the end cap is used for probes, both holes are pierced out, otherwise one hole is pierced out for cables. These end caps are made out of coloured ABS plastic. A small hand operated injection moulder was used to manufacture them.

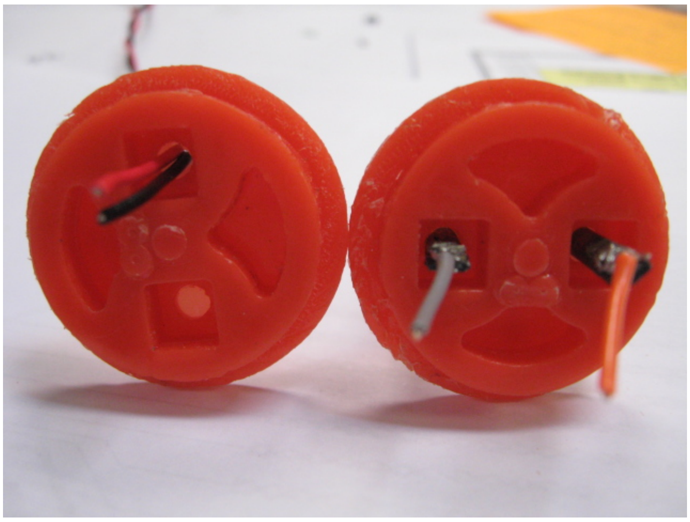


Figure 52: Soil Moisture Sensor's End Caps

The two probes are made from stainless steel to prevent corrosion. These probes are 15mm apart and 150mm long. The probe connections are sealed with noncorrosive silicon glue. Once all the circuit is fitted into the tube, both end caps are sealed with noncorrosive silicon glue as well. Noncorrosive silicon glue was used to prevent deterioration of solder joints and copper tracks on the PCB.

6.6 Soil Moisture Sensor Hardware Calibration

There are two types of calibration procedures to be followed, hardware calibration and software calibration. For hardware calibration, the initial operating frequency was set up to correct frequency range. For the software calibration, the frequency versus soil moisture graph was plotted and the best fit line was calculated.

The initial hardware calibration is achieved by adjusting the variable inductor core to obtain an oscillator frequency of 18.75MHz in a dry soil sample. When the sensor is placed into a fully wet water beaker, the frequency drops to 16.4MHz (refer to Figure 53). For the initial calibration, a Tektronic TDS20123 oscilloscope was used.

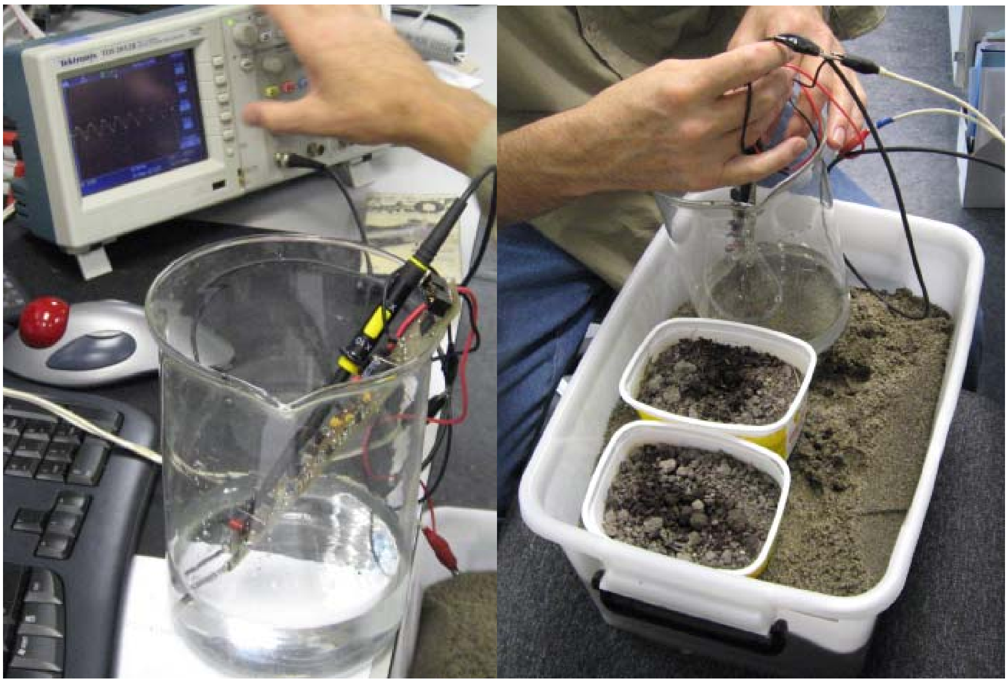


Figure 53: Sensor Initial Calibration

7 Results and Software Calibration

The first prototype soil moisture sensor units have been developed at Auckland University of Technology, New Zealand. A test mesh network was established with four router nodes and one coordinator node. This was used to test the system communications. Due to the micro scale soil moisture measurement requirement, a 100m grid network was used. The communication range of the wireless unit is 120m in an open area. According to the user's requirements, data was recorded at 1 minute intervals. This data recording interval can be adjusted according to the user's requirements. The communications test was successful.

7.1 Calibration with Off-the-Shelf Soil Moisture Meter

The microcontroller software soil calibration was performed by comparing with an off-the-shelf soil moisture sensor (Delta-T Devices HH2) (refer to Figure 55). Both the Delta-T HH2 soil moisture sensor and the capacitive soil moisture sensor were placed into the same soil sample and the frequency from the capacitive sensor was recorded against the measured soil moisture level from the Delta-T HH2 soil moisture sensor. Once data is recorded, the relationship between the frequency output and soil moisture level can be formulated and programmed into the ATmega 16 micro controller (refer to Table 3).

In order to record the data from the commercial Delta-T HH2 soil moisture sensor, two dry samples were used (clay and sand). For each reading 20 mL of water was added to each sample and measured the actual weight of the sample and same time soil moisture percentage was measured using Delta-T HH2 meter. There were 12 readings were taken. To measure the weight of the samples, the Satrue SK-2000H digital scale was used.

Total Volume = 432 mL is constant.

	Actual data with weight		Measured Data from HH2	
No. Readings	**Added Water (mL)**	**%Vol**	**Sand**	**Clay**
1	20	4.63	Out of Range	Out of Range
2	40	9.26	Out of Range	Out of Range
3	60	13.89	2	0.1
4	80	18.52	5.1	1.9
5	100	23.15	9	2.4
6	120	27.78	17.6	4.7
7	140	32.41	21	10.8
8	160	37.04	26.5	20.3
9	180	41.67	33.9	27.4
10	200	46.30	36.7	29.2
11	220	50.93	39	30.2
12	240	55.56	40.4	31

Table 3: Measured Data from HH2 Soil Moisture Meter

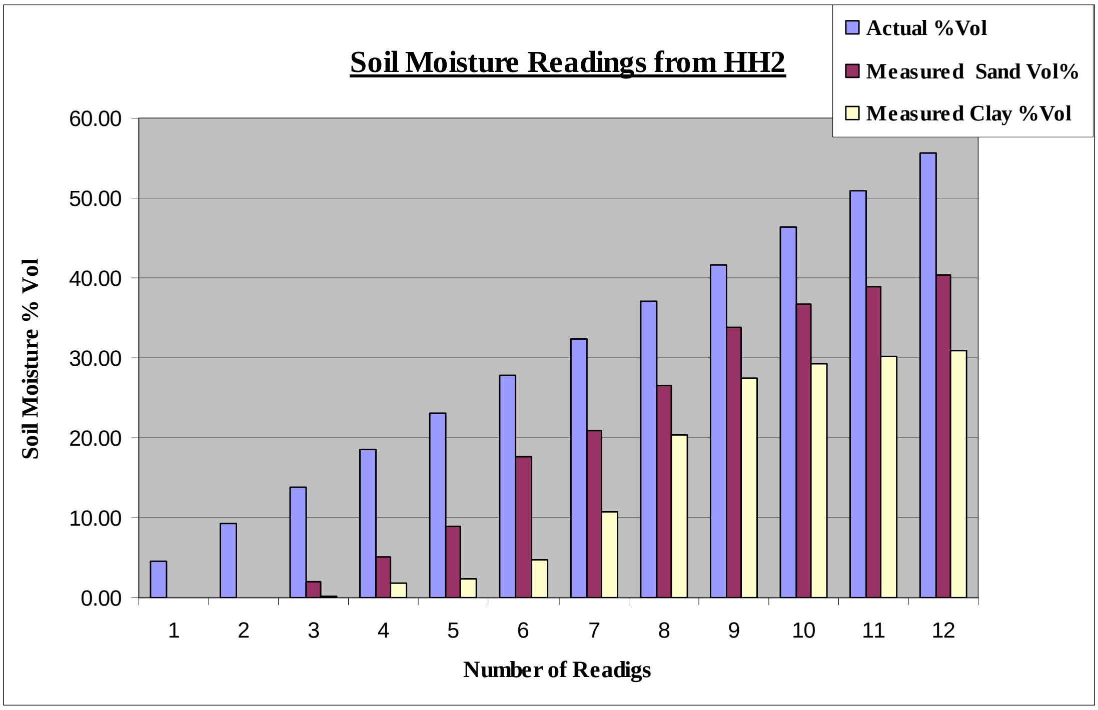


Figure 54: Soil Moisture % Volume Reading from HH2 Meter

Figure 55: Delta-T HH2 Commercial Soil Moisture Sensor

It has been found that the commercial soil moisture meter has a limited range. Moreover it has less sensitivity at the lower range of soil moisture content. When the measured data and actual data weight volume are compared, the meter reading is wrong by 10 to 20 % volume units. Therefore the experiment of method had to be changed. The new testing method was to weigh the soil sample and add a known weight of water so the actual moisture content could be reliably estimated over a wide range of values.

7.2 Soil Moisture Sensor Calibration

Software calibration was achieved by comparing the calculated soil moisture percentage (by volume) with the output frequency of the soil moisture sensor. The setup of the experiment used two known dry soil samples (clay and sand) placed into identical containers (both having same volume). A known amount of water was added incrementally until saturation. The frequency and the weight of the samples were measured for each increment. The Satrue SK-2000H digital scale was used to measure the weight. In each increment, after water is added to the soil, it needs to be mixed thoroughly, in order to obtain a uniform spread of soil and water in the sample.

Once data was collected, a third container was filled with distilled water, and the weight of the water was measured. Then the density of the dry soil samples (clay and soil) was calculated.

The first five readings were taken with 10mL water increments and the rest of the readings used 20mL water increments, until saturation.

According to the experiment, the sand sample reached saturation at 25.77% volume. The clay sample reached to saturation at 34.74% volume. The frequency variation of the soil moisture sensor for the sand sample from fully dry to totally saturated, was 2.7 MHz to 0.43 MHz. Similarly clay sample had frequency range of 2. 73MHz to 0.412MHz. These frequencies are measured after down conversion.

Total Volume = 432 mL is constant.

Soil		Frequency (MHz)	
Added Water (mL)	**% Vol**	**Clay**	**Sand**
10	2.31	2.73	2.7
20	4.63	2.51	2.35
30	6.94	2.25	2.24
40	9.26	1.66	2.16
50	11.57	1.58	2.07
70	16.20	1.38	2
90	20.83	1.25	1.87
110	25.46	1.22	1.72
130	30.09	1.01	1.3
150	34.72	0.815	0.43
170	39.35	0.65	0.43
190	43.98	0.57	0.43
210	48.61	0.51	0.43
230	53.24	0.412	0.43

Table 4: Soil Moisture Meter Results

The soil percentage volume and frequency output of the soil moisture sensor for each sample was plotted. Both samples showed the same trend. As the moisture content increased the output frequency of the sensor decreased. The clay and sand have different saturation points. This is due to the ability of water absorption of the soil type. For example, sand would hold a minimum amount of water between sand particles, but on the other hand clay holds more water between clay particles clay it holds water like a sponge. Therefore clay has a saturation point of 34.74% volume and sand has a saturation point of 25.77% volume.

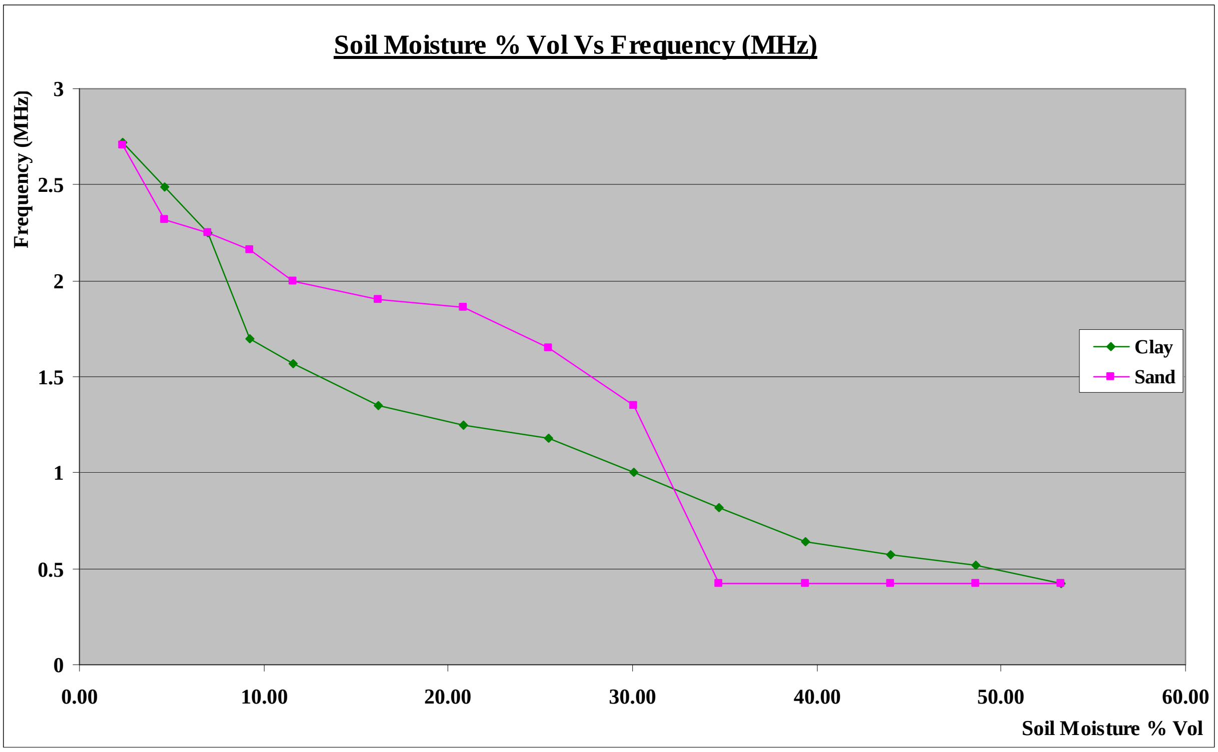


Figure 56: Soil moisture % Volume Vs Output Frequency

Figure 56 above shows the behaviour of the soil moisture sensor for the two different soil samples (sand and clay). The samples have different water holding properties. At the start, both soils show the same frequency output, but as water % volume increased, the different soil types produced different frequency effects with water. Therefore there is a separation between the two curves as water % volume increases. Once the samples reach saturation point, the two graphs tend to merge.

The main reason for the capacitance difference between the sand and clay samples can be explained by using the properties of the samples. When water is added to the sand sample water tends to seep to the bottom of the container, due to the solid crystal profile of the sand. Therefore the capacitive readings tend to show a faulty representation of the true soil moisture percentage volume. On the other hand clay has a fine soft profile, which can absorb and retain water within the soil partials. Hence the clay sample tends to show a true representation of the soil moisture percentage in soil.

Due to this effect the commercial meter uses separate calibration graphs for each soil type. Therefore more accurate output data can be produced. The down side of this approach is the operator needs to have a broader understanding of soil types. But in this application the soil moisture sensor needs to be simple, cost effective and most importantly it should be able to operate under any soil samples with little understanding of soil. Therefore output readings need to be scaled and generalised. A separate generalised graph needs to be formulated to operate for most soil samples reasonably accurately to understand the soil moisture content, in order to control the irrigation.

According to the Ya. Pachepsky, W. Rawls, D. Gimenéz and J. P. C. Watt [46] research, it was found around New Zealand most soil has a statistical mean of 22.8% of sand, 53.8% of silt and 23.4% of clay content (refer to Table 5). Hence average soil around New Zealand contains 77.2% of mixture of clay and silt, therefore the performance of the soil moisture sensor is closer to the clay curve on Figure 56.

Statistics	Soil parameters Sand content (%)	Silt content (%)	Clay content (%)	Bulk density (g cm^{-3})
Mean	22.8	53.8	23.4	1.36
Standard deviation	17.9	12.2	10.3	0.18
Minimum	1.0	11.0	3.0	0.89
Maximum	86.0	70.0	54.0	1.76
Volumetric water content at	0 kPa	−5 kPa	−10 kPa	−20 kPa
Mean	0.485	0.379	0.351	0.324
Standard deviation	0.066	0.069	0.078	0.091
Minimum	0.340	0.200	0.080	0.060
Maximum	0.660	0.570	0.560	0.560

Table 5: Statistics of Soil Parameters in Soil [46]

In order to generalise the soil moisture curve, it is necessary to understand the relationship between oscillator frequency and the change in sensor capacitance caused by soil moisture. Therefore a series of real capacitors were placed between soil moisture sensor probes and output frequency of the oscillator was measured (refer to Table 6 and Figure 57).

Capacitance (pF)	Oscillator Output MHz
2.2	18.43
4.7	18.08
10	17.77
22	17.33
47	16.88
100	16.63
220	16.49
470	16.47
1000	16.4

Table 6: Oscillator Output Frequencies and Capacitor Values

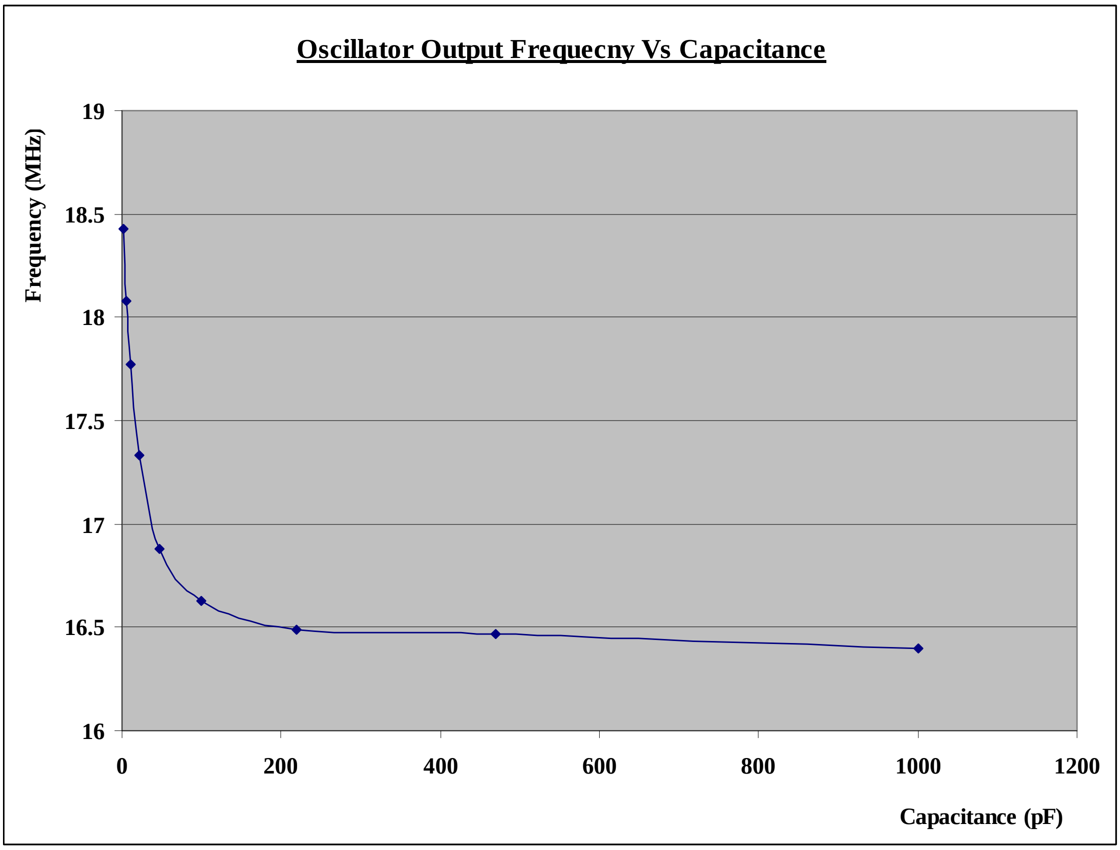


Figure 57: Oscillator Output Vs Capacitance

As the capacitance increases, the loading on the oscillator increases causing a damping effect on the oscillator. If the capacitance increases any further, the oscillator will stop functioning due to too much loading. The Figure 57 shows how the oscillator responds with increasing capacitance.

It was found that after 23% volume of soil moisture, the soil is close to saturation, and also the readings are not so useful for a vineyard management system. Moreover the oscillator readings are not stable due to the damping effect on the oscillator. Therefore it was decided to use the range of 0% to 24% for the soil moisture sensor.

In order to understand the relationship between the capacitance and soil moisture % volume at 16 MHz, the capacitance values corresponding to measured frequencies were calculated from the Table 6, and substituted into Table 4for the corresponding soil moisture % volumes (refer to Figure 58and Table 7).

Total Volume = 432 mL is constant.

Soil Moisture		**Frequency (MHz)**		**Capacitance (pF)**	
Added Water (mL)	**% Vol**	**Clay**	**Sand**	**Clay**	**Sand**
10	2.3	2.73	2.7	0.1	0.3
20	4.6	2.51	2.35	1.6	2.8
30	6.9	2.25	2.24	3.5	3.6
40	9.3	1.66	2.16	13.0	4.1
50	11.6	1.58	2.07	15.2	4.9
70	16.2	1.38	2	20.6	6.1
90	20.8	1.25	1.87	26.4	8.3
110	25.5	1.22	1.72	28.1	11.4
130	30.1	1.01	1.3	39.8	23.7
150	34.7	0.815	0.43	60.8	772.9
170	39.4	0.65	0.43	95.8	772.9
190	44.0	0.57	0.43	151.4	772.9
210	48.6	0.51	0.43	202.9	772.9
230	53.2	0.412	0.43	909.1	772.9

Table 7: Capacitance value for Corresponding Soil Moisture Values

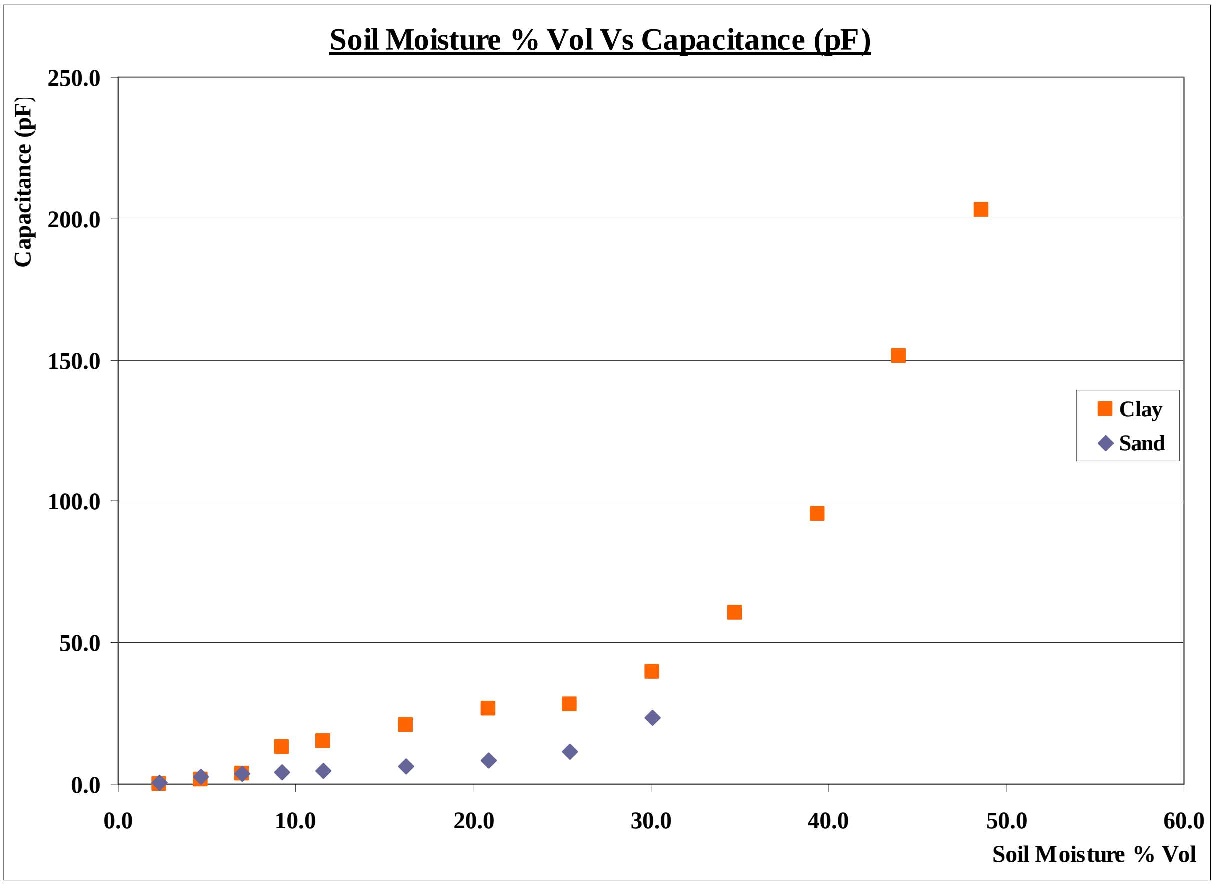


Figure 58: Soil Moisture % Volume Vs Capacitance

The moisture values above 24% are not useful and less accurate. The reduced range of soil moisture percentage volume and capacitance values are plotted on Figure 59. These reduced ranged values can be used to find the relationship between soil moisture content and capacitance.

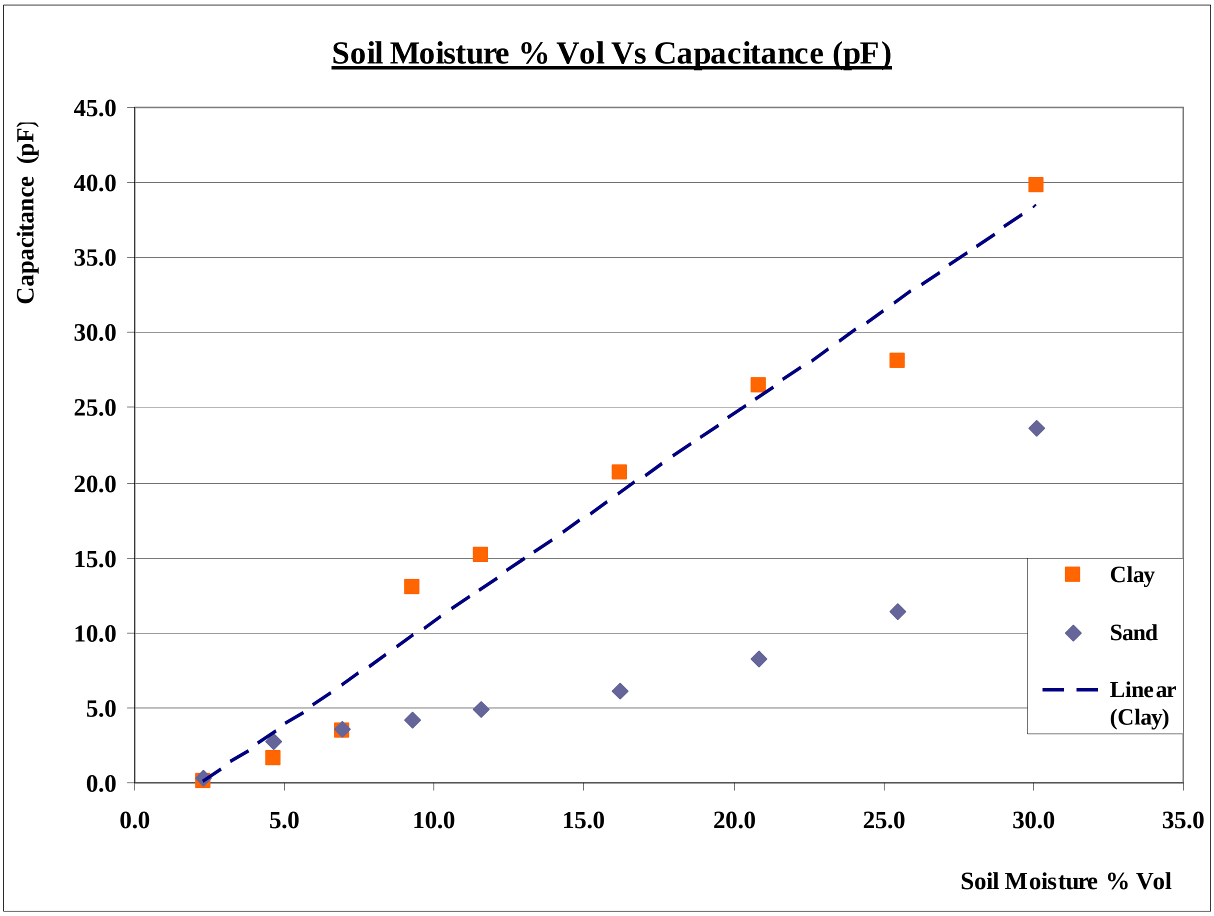


Figure 59: Useful Range for Soil Moisture % Volume Vs Capacitance

It can be seen that over this range of soil moisture %, the variation of capacitance with soil moisture % is approximately a straight line.

The relationship can be written as:

$$y = 1.38\,x - 3.06 \tag{12}$$

The constants are obtained by fitting a straight line to the data.
Where:
y is Capacitance in pF
x is Soil Moisture % volume

Therefore:

$$\text{Soil Moisture \% volume} = \frac{\text{Capacitance} + 3.06}{1.38} \tag{13}$$

Once frequency is measured soil moisture % value can be calculated using equation 14. The soil moisture % is calculated by finding the interpolating between, the appropriate range of frequency points in the calibrated soil moisture % and frequency table (refer to Table 4).

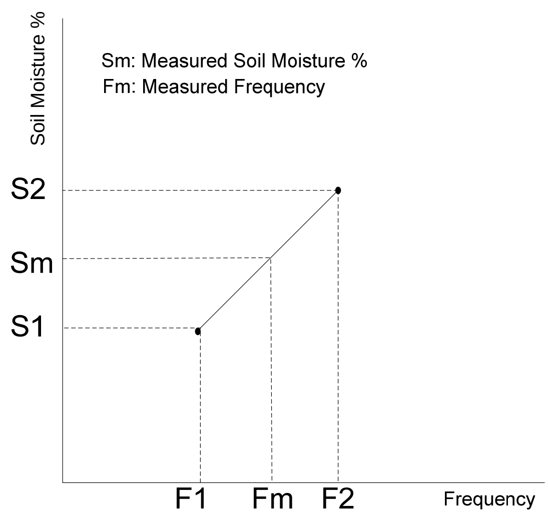


Figure 60: Soil Moisture % Calculation Method

$$SoilMoisture\% = S_1 + (S_2 - S_1) \times \frac{F_{measured} - F_1}{F_2 - F_1} \tag{14}$$

In the final software calibration, the useful part of the Table 4 (up to 30% of soil moisture %) is included into the microcontroller as a look up table. The equation 14 is used to calculate the soil moisture percentage volume between appropriate points.

8 Future Plans

The design work for the third generation of micro climate weather station has been started. In this revision modular sensor architecture is proposed.

8.1 System Improvements

The system can be improved by introducing a frost management system. The existing dew point prediction system and vineyard sprinkler system can be integrated to protect the vineyard from frosts and at same time can be used to optimise the irrigation requirements.

The existing micro climate weather station has temperature and humidity sensors to predict the dew point. Almost all vineyards have an irrigation sprinkling system. In later stages, irrigation control hardware can be designed to control the sprinklers from the sensor nodes. The system control can be organised from the main computer and router nodes can control the sprinkler system valves via the wireless sensor network (refer to Figure 61).

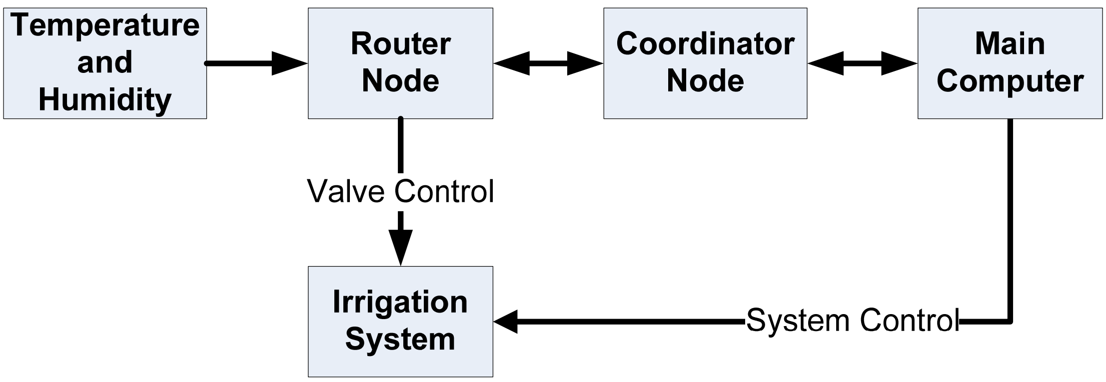


Figure 61: Frost Protection and Irrigation System

This system can be optimised to save water by predicting frost and controlling irrigation needs during periods of frost. This system can be used to reduce the operating cost of a vineyard.

8.2 Hardware and Software Improvements

A modular architecture minimises the software upgrade down time and enables hardware reusability. A modular design allows greater flexibility for the end product. The same node can be utilised for different applications when equipped with the required sensor modules. This is highly desirable when each sensor node collecting microclimate, atmospheric and plant data in different vineyards requires a different sets of sensors.

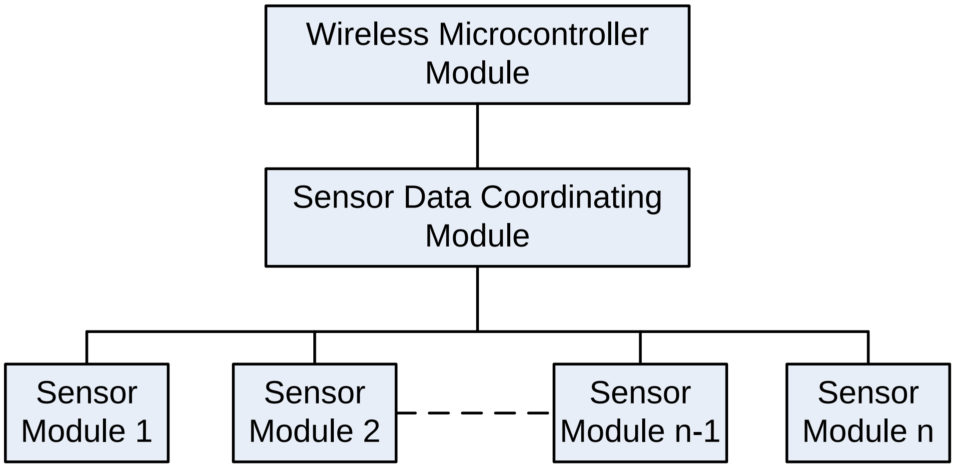


Figure 62: Components of proposed modular sensor architecture [48]

Figure 62 illustrates the building blocks of the proposed modular sensor design. The wireless microcontroller module controls the data communication aspect, while the sensor data coordinating microcontroller module, collects and calibrates the data. It is then possible to introduce various types of sensor modules required by different applications [48].

This design allows for including up to 16 different sensor modules and two controller modules. Some sensors such as soil moisture and leaf wetness are externally exposed pluggable modules and others are embedded into sensor cards. There are two levels of controller modules, board level controller and communication level controller. The Atmel ATmega1281 microcontroller will be used for board level communication. This powerful microcontroller contains

16 Analogue to Digital Converter (ADC) channels and 4 UART ports. This microcontroller can operate up to 16MHz at 5VDC [48].

The main aim of this board level controller unit is to maintain the interfacing between different sensor modules and transfer the processed data to the communication level controller module via a UART communication port. The power management of the sensor modules is monitored by the ATmega1281 microcontroller. The power management is achieved by shutting down sensors when they are not in service. The service time will be defined by either a pre-allocated time interval or a request from the main coordinator unit. When the units are run in pre-allocated time mode, the microcontroller extracts the reading from the sensor module at defined intervals. The second mode is an interactive process between the coordinator and router nodes. The coordinator nodes can request data from each individual router node, according to the user inputs [48].

Each sensor module consists of its own card, as shown in Figure 63. The main advantage of this design is that all the sensor modules are interchangeable. Each sensor card has a unique 8- bit ID number. Therefore when the card is plugged into any slot, the main microcontroller will identify the ID number and set the calibration setting for the specific card. This modular design will support the expansion of new sensor modules and also the sensing unit can be optimised for any specific application [48].

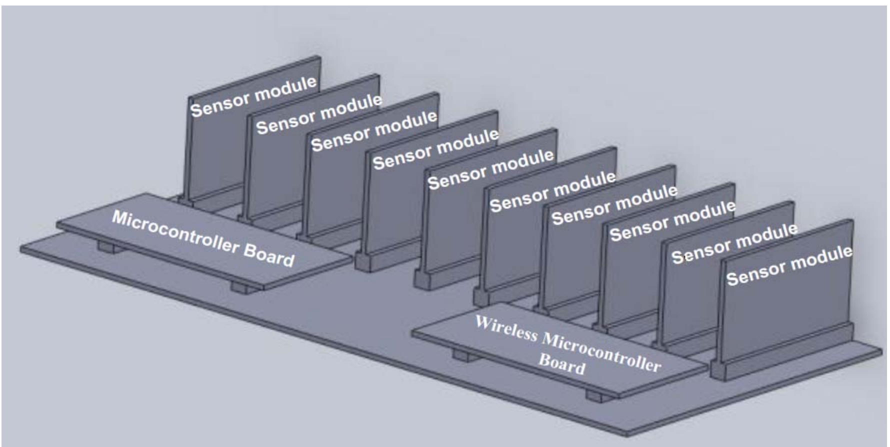


Figure 63: Modular board with plug-in sensor cards [48]

8.3 Second Generation Soil Moisture Sensor

The second generation soil moisture sensor is a recommended future design, in order to simplify the electronic design. This recommended new design does not have the down convertor and oscillator and comparator stages. This design will have a LC resonant circuit, 8 MHZ sine wave source, diode rectifier and two buffer and filter stages (refer to Figure 64).

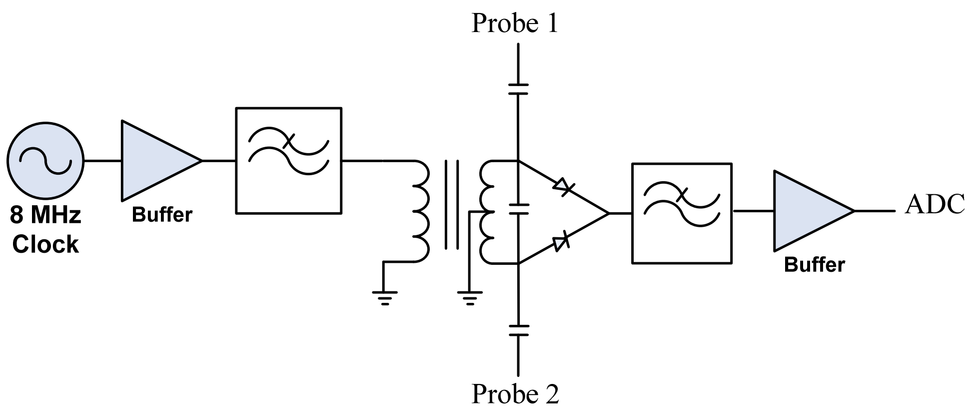


Figure 64: Second Generation Soil Moisture Sensor

Initially the LC resonant circuit is tuned to produce maximum amplitude in dry soil. Then when the probes are placed in damp soil, the LC resonant frequency will shift and measured amplitude will drop (refer to Figure 65). This decreasing amplitude is measured using the ADC.

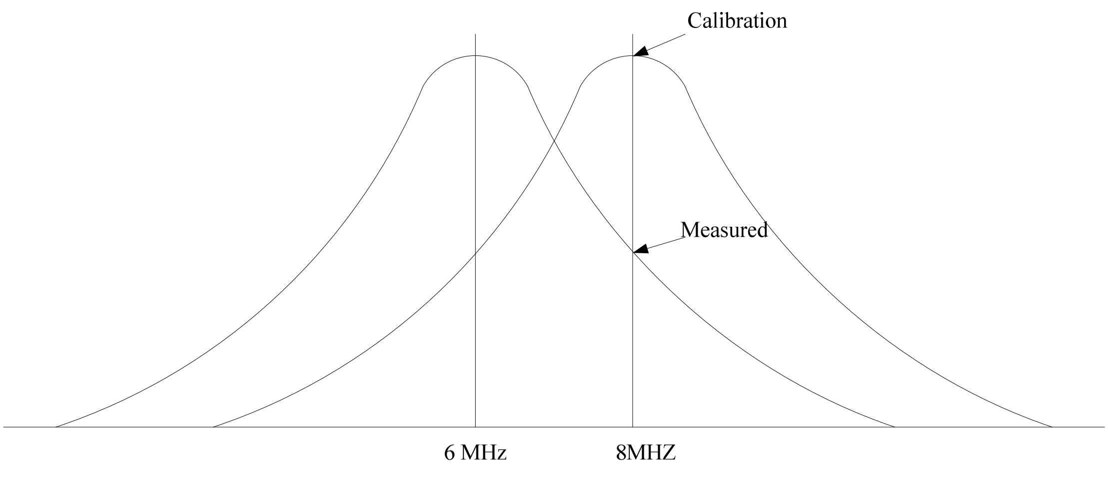


Figure 65: LC Resonant Circuit's Amplitude

9 Discussion and Conclusion

This research has described the design and construction of a soil moisture sensor and wireless micro climate weather station, which collects environmental data to improve vineyard management. By improving vineyard management the use of water and energy and ultimately overall yield can be optimised.

An IEEE802.15.4/ZigBee wireless network is used to transmit the data from sensor nodes to the main base station. The mesh networking topology was used to increase the reliability and scalability of the system.

The Texas Instrument CC2430 ZigBee ready microcontroller is used as the wireless sensor hardware. Because TI provides the IEEE 802.15.4/ZigBee stack, the development time for the software application layer is short. This was the main reason for selection of the TI 8051 architecture based wireless microcontroller.

In wireless sensor node hardware design, a modular pluggable wireless microcontroller board was designed. The module was used in both the coordinator and router nodes. The coordinator node is used to collect the data from the network. The router node is used collection data from sensors and transmits the data to the coordinator node via the mesh network.

After investigating different soil moisture measuring techniques, a capacitive soil moisture sensor design was selected for the hardware development. The main reasons for the selection were that, this type of sensor has a higher accuracy and a lower development cost than other. It is most suitable for continuous data logging systems like wireless sensor networks [49].

Understanding of vineyard management is one of the key aspects of this research, in order to improve the operation of the vineyard to optimise the yield. There are two main areas which can be improved by introducing a microclimate weather station. The first area is frost prediction. If frost can be predicted in a local area in advance, damage to the vineyard can be minimised by taking preventive actions locally rather than over the whole vineyard. The second area is irrigation. By monitoring soil moisture content, irrigation to the plants can be controlled, according to the stage of growth of the plants. Also irrigation can be restricted to the local area rather than being applied to the whole vineyard.

Finally in vineyard management, the whole management structure can be improved in future work, by combining the frost prediction system and the soil moisture system. Once frost is predicted, irrigation sprinklers can be used to prevent frost, and at the same time soil moisture can be monitored to operate the sprinklers until the required soil moisture level is reached. By introducing these two systems, vineyard management can be improved further.

The series fed Hartley oscillator was used to measure the soil moisture content. This is first time this type of circuit has been used to measure soil moisture content. In previous research projects normal Hartley, Colpitts or Clapp oscillator have been used. The series fed Hartley oscillator is more suitable for BJT based oscillator design. It also provides good impedance matching over a wide range of frequencies.

The soil moisture sensor was tested with two different soil samples (clay and sand). It was found clay and sand follow same trend line but have slightly different frequency values. This was caused by the capacitive effect of water mixed with sand and water mixed with clay. Most commercial meters use different calibration graphs for different soil types. But in this research soil moisture sensor needs to be simple and easy to install. Therefore final data was scaled according to the Ya.Pachepsky's [46] research result.

The work for a third generation micro climate weather station has already been started. The new design is going to have a modular structure, to promote serviceability, software improvement and flexibility of the system. In the new design, a sensor power and data management layer will be introduced to enhance the energy conservation and efficiency of the system. This system can be improved in the future by combining frost prediction and an irrigation management system to optimise the vineyard management.

Reference

1. Xianghui Cao, J.C., Yan Zhang, and Youxian Sun, *Development of an integrated wireless sensor network micro-environmental monitoring system.* ISA Transactions, July 2008. **47**(3): p. 247-255.

2. Camilli, A., Cugnasca, C. E., Saraiva, A. M., Hira-kawa, A. R., and Corrêa, P. L., *Anatomy of an application for precision agriculture Computers and Electronics in Agri-culture.* wireless sensors to field mapping, August 2007. **58**(1): p. 25-36.

3. Sallis, P.J., Shanmuganathan, S., Pavesi, and L., and Jarur, M. *"A system architecture for collaborative envi-ronmental modelling research"*. in *International Symposium on Collabora-tive Technologies and Systems (CTS 2008)*. May 19-23 2008. Irvine, California: A publication of the IEEE, New Jersey, USA.

4. Maxwell, J.C., *A Treatise on Electricity and Magnetism.* Agronomy journal,, March-April 2001. **93**: p. 68-73.

5. Jose', D. and A. Gutierrez, *IEE Std. 820.15.4 Enabling Prevasive Wireless Sensor Networks.* Innovation Centre, 2005.

6. Young Hun, S., et al. *Performance evaluation of wireless networked control system using time-triggered IEEE 802.15.4*. in *ICCAS-SICE, 2009*.

7. Hyung Seok, K., S. Joo-Han, and L. Seok, *Energy-Efficient Traffic Scheduling in IEEE 802.15.4 for Home Automation Networks.* Consumer Electronics, IEEE Transactions on, 2007. **53**(2): p. 369-374.

8. Egan, D., *The emergence of ZigBee in building automation and industrial control.* Computing & Control Engineering Journal, April-May 2005 **16**(2): p. 14-19.

9. Garcia, R.R., *Understanding the Zigbee stack.* 02/01/2006(Freescale Semiconductor Inc.).

10. Wheeler, A. *ZigBee Wireless Networks for Industrial Systems - White Paper*. 2006 [cited 04/09/2007]; Available from: http://www.microcontroller.com/Embedded.asp?did=149.

11. *Soil Moisture Measurement Methodology*, in *Pacific Region Pocket Handbook*, USDA - SCS - E–15 and Water Management Note-Estimating soil moisture by feel and appearance, High Plains Underground Water Conservation District No. 1.

12. *Soil Science Instrumentation*. 2003-2009 [cited 10/01/2010]; Available from: http://www.ictinternational.com.au/soils.htm.

13. Henebry, G.M. and A.K. Knapp. *Spatio-temporal dynamics of soil moisture in tallgrass prairie using ERS-1 SAR image time series: first year results*. in *Geoscience and Remote Sensing Symposium, 1996. IGARSS '96. 'Remote Sensing for a Sustainable Future.', International*. 1996.

14. Saïd, M.N., *Moisture Measurement Guide for Building Envelope Applications.* Building Envelope and Structure Program Institute For Research in Construction National Research Council Canada, 2004: p. 4-15.

15. Lamb D, *Vineyard monitoring and management beyond 2000*. 2000, National Grape & Wine Industry Centre, Charles Sturt University: Wagga Wagga, NSW.

16. Ghobakhlou, A., S. Shanmuganthan, and P. Sallis, *Wire-less sensor networks for climate data management systems.* 18th IMACS World Congress - MODSIM09 International Congress on Modelling and Simula-tion, July 2009,: p. 959-965.

17. Ghobakhlou A., Perera A., Sallis P., Diegel O., Zandi S. , *Environmental Monitoring with Wireless Sensor Network.* The sixteenth Electronics New Zealand Conference 18-20 November 2009: p. 18-20.

18. Suri, A., S.S. Iyengar, and E. Cho, *Ecoinformat-ics using wireless sensor networks: An Overview. Ecological Informatics.* November 2006. **1**(3): p. 287-293.

19. Snyder, R.L. and J.P.d. Melo-Abreu, *Frost Protection: fundamentals, practice and economics.* Food and Agricultural Organization of the United Nation, Rome, 2005. volume 1.

20. Domoto P. *Methods of Vineyard Frost Protection*. in *Iowa Wine Growers Association Annual Meeting*. January 2006. Iowa: Department of Horticulture Iowa State University.

21. Sonntag D., *Important New Values of the Physical Constants of 1986,.* Vapour Pressure Formulations based on the IST-90 and Psychrometer Formulae; Z. Meteorol, 1990. 70(5): p. 340-344.

22. SENSIRION, *Application Note Dew-point Calculation.* October 2006: p. 1-3.

23. Hardy B. *Thunder Scientific Corporation, Albuquerque, NM, USA*. in *The proceedings of the Third international Symposium on Humidity & Moisture*. April 1998. Teddington, London, England.

24. Williams L. E. *Irrigation of Winegrapes in California*. December 2001 [cited 6/03/2010]; Department of Viticulture & Enology University of California-Davis, and Kearney Agricultural Center:[Available from: http://www.practicalwinery.com/novdec01p42.htm.

25. Peacock W.L., Williams L.E., and C. L.P., *Water management and irrigation scheduling*, in *L.P. Christensen (ed.) Raisin Production Manual*. 2000, DANR Publications: Univ. California, Oakland,CA. p. 127-133.

26. Goldhamer D. A. and S.R. L., *Irrigation scheduling. A guide for efficient on-farm water management*. 1989, DANR Publication 21454: University of California, Oakland, CA. p. 67.

27. Williams, L.E., Dokoozlian N. K., and W. R., *Handbook of Environmental Physiology of Fruit Crops*, S. B. and A.P. C., Editors. 1994, CRC Press: Orlando, FL. p. 83-133.

28. Oldhamer D.A. and F. E., *Simplified tree water status measurements can aid almond irrigation.* California Agriculture, 2001. **55**(3): p. 32-27.

29. Bogena H.R., et al., *Evaluation of the ZigBee based wire-less soil moisture sensor network SoilNet*, in *Kommissionen I, VI und VIII der DBG*. 2008, Berichte der DBG: Jülich, Germany.

30. Sulaiman, S., A. Manut, and A.R.N. Firdaus. *Design, Fabrication and Testing of Fringing Electric Field Soil Moisture Sensor for Wireless Precision Agriculture Applications*. in *Information and Multimedia Technology, 2009. ICIMT '09. International Conference on*. 2009.

31. Anurag D, Siuli R., and S. B., *AGRO-SENSE: PRECISION AGRICULTURE USING SENSOR-BASED WIRELESS MESH NETWORKS*. 2008: Indian Institute of Management Calcutta, India.

32. Ruiz-Garcia L., et al., *A Review of Wireless Sensor Technologies and Applications in Agriculture and Food Industry: State of the Art and Current Trends.* Sensors, 2009. **9**.

33. Jzau-Sheng, L. and L. Chun-Zu. *A monitoring system based on wireless sensor network and an SoC platform in precision agriculture*. in *Communication Technology, 2008. ICCT 2008. 11th IEEE International Conference on*. 2008.

34. Valente, A., J. Boaventura Cunha, and C. Couto. *Soil moisture sensor with built-in fault-detection capabilities*. in *Industrial Electronics Society, 1998. IECON '98. Proceedings of the 24th Annual Conference of the IEEE*. 1998.

35. Yamamoto, Y. and A. Ogawa. *Novel soil-moisture-sensors applying thermal characteristics of soil and water*. in *Sensors, 2002. Proceedings of IEEE*. 2002.

36. Wobschall, D., *A Frequency Shift Dielectric Soil Moisture Sensor.* Geoscience Electronics, IEEE Transactions on, 1978. **16**(2): p. 112-118.

37. Boyapati P. and Shenai K., *A Novel Wireless Soil Moisture Sensor*, in *INTERNATIONAL CONFERENCE ON ENERGY AND ENVIRONMENT*. MARCH 19-21, 2009: India. p. 288-290.

38. Wallace R., *Antenna Selection Guide*, in *Application Note AN058*. 2009, Texas Instruments: Texas.

39. Jonsrud G. E., *Folded dipole antenna for CC2400, CC2420, CC2430, CC2431, and CC2480*, in *Application Note AN040*. 2008, Texas Instruments Incorporated: Texas.

40. Coyte C., M. Beckerlet, and J.D. Collins, *Spike: A Six Legged Cube Style Robot*, in *Second International conference ICIRA Intelligent Robotics and Applications* M. Xie, et al., Editors. 2009, Springer: Singapore. p. 535-544.

41. Prince-Pike A., *Power Characterisation of a Zigbee Wireless Network in a Real Time Monitoring Application*, in *School of Engineering*. 2009, Auckland University of Technology: Auckland. p. 132.

42. J. E. Campbell, *Dielectric Properties and Influence of Conductivity in Soils at One to Fifty Megahertz.* Soil Sci. Soc. Am. J, 1990. **54**.

43. Selig E. T and S. Mansukhani, *Relationship of soil moisture to dielectric properties.* J. G. T. ASCE,, 1975. **101**: p. 760-770.

44. Johnson, P.M., D.V. Thiel, and D.A. James. *Contributions to the measured capacitance by the dielectric properties of water in insulated electrode soil moisture sensors*. in *Sensors, 2002. Proceedings of IEEE*. 2002.

45. Perera T.A.S.A and J.D. Collins. *Wireless Soil Moisture Sensor for Vineyard Soil Monitoring*. in *The sixteenth Electronics New Zealand Conference*. 2009. Dunedin.

46. Ya. Pachepsky, W.R., D. Gimenéz , J. P. C. Watt, *Use of soil penetration resistance and group method of data handling to improve soil water retention estimates* Soil and Tillage Research, November 1998. **49**(1-2): p. 117-126.

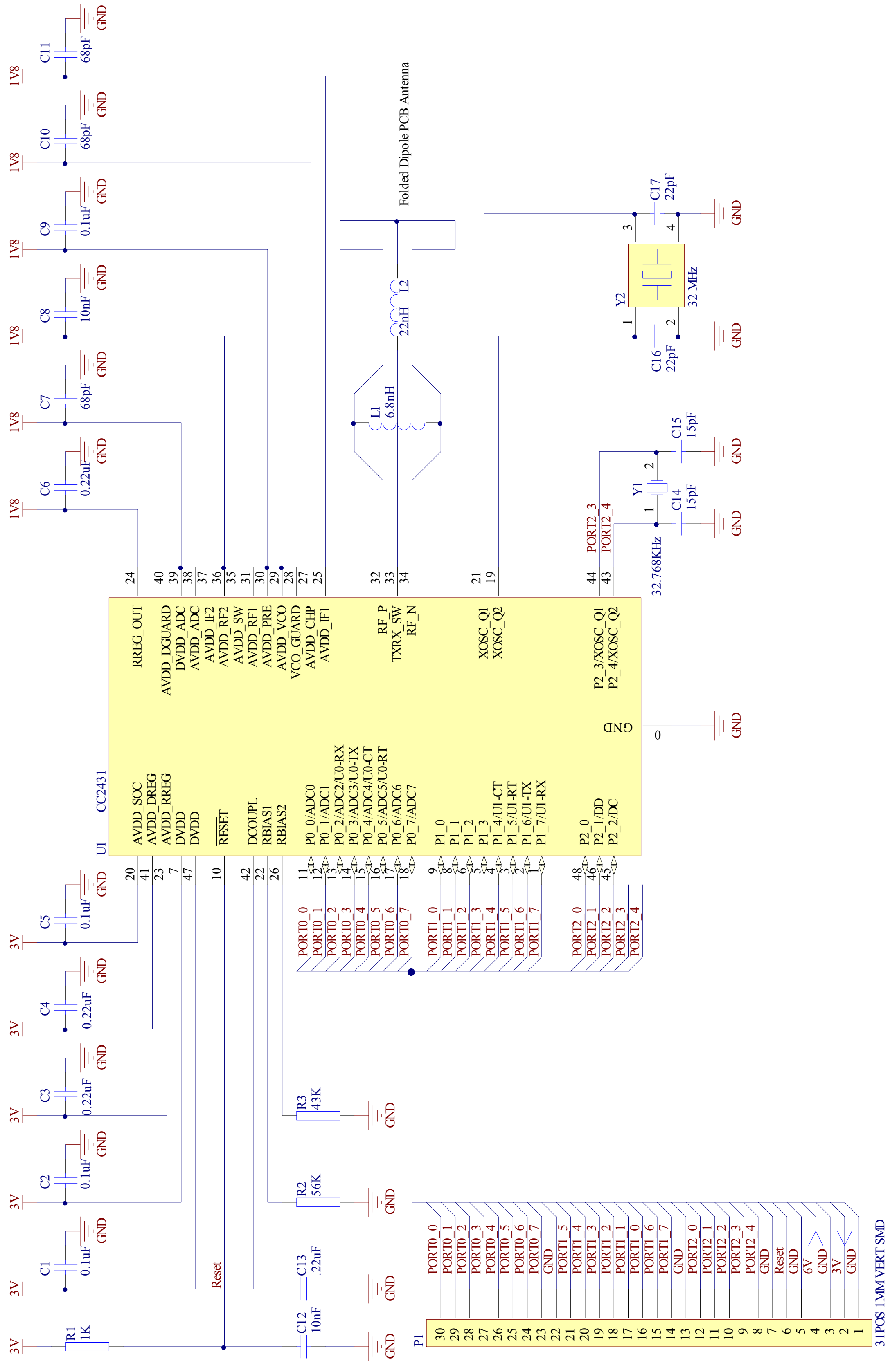
47. Bosch, D.D., *Comparison of Capacitance-Based Soil Water Probes in Coastal Plain Soils.* Vadose Zone Journal, 2004. **3**: p. 1380-1389.

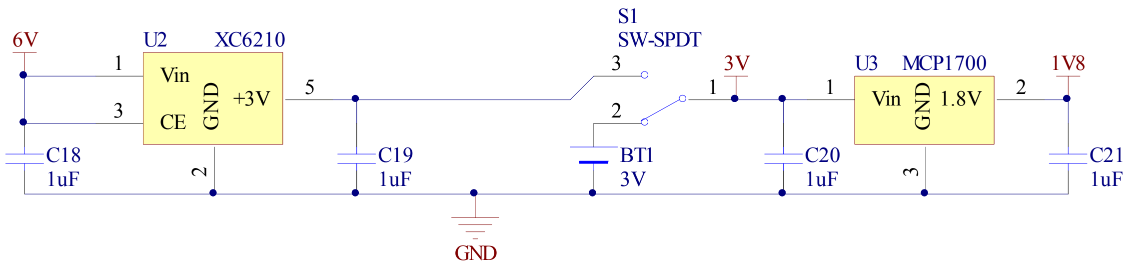
48. Ghobakhlou A., Perera A., Sallis P., Zandi S. , *Modular Sensor Nodes for Environmental Data Monitoring*, in *4th International Conference on Sensing Technology (ICST 2010)*. June 2010: Lecce,Italy.

49. Cataldo, A., et al. *Time Domain Reflectometry Technique for Monitoring of Liquid Characteristics*. in *Instrumentation and Measurement Technology Conference, 2005. IMTC 2005. Proceedings of the IEEE*. 2005.

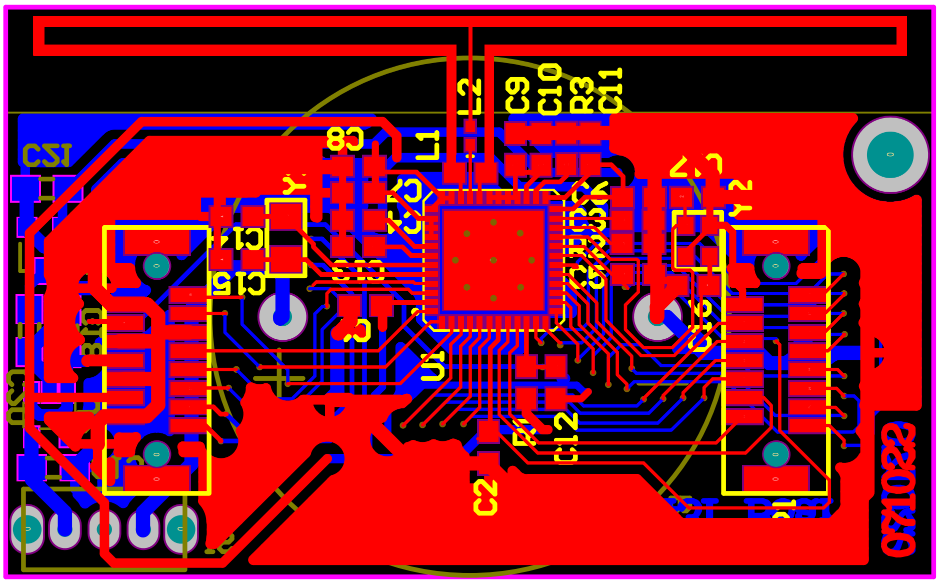
Appendix A – ZigBee and Sensor Circuit Designs

CC2430 wireless microcontroller module schematics

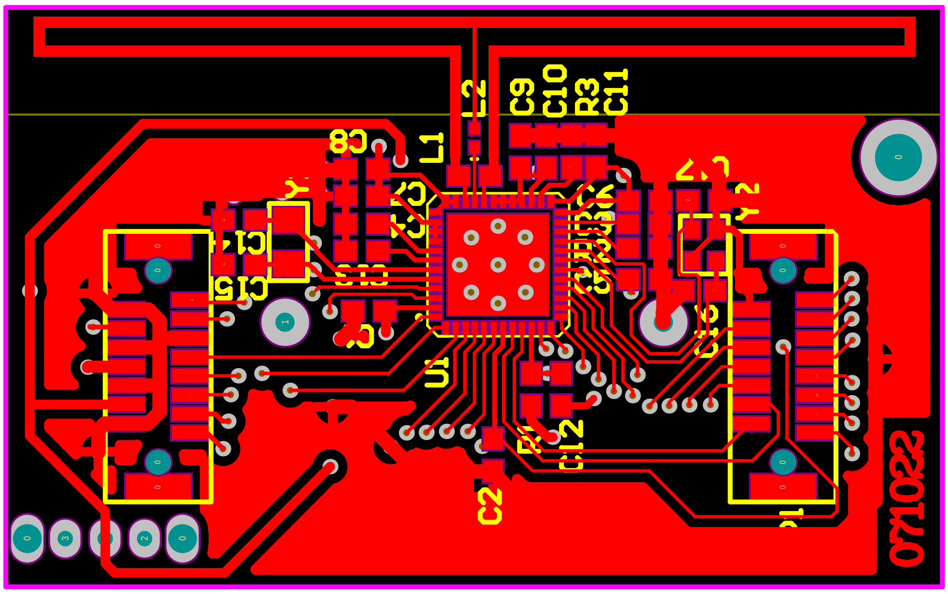




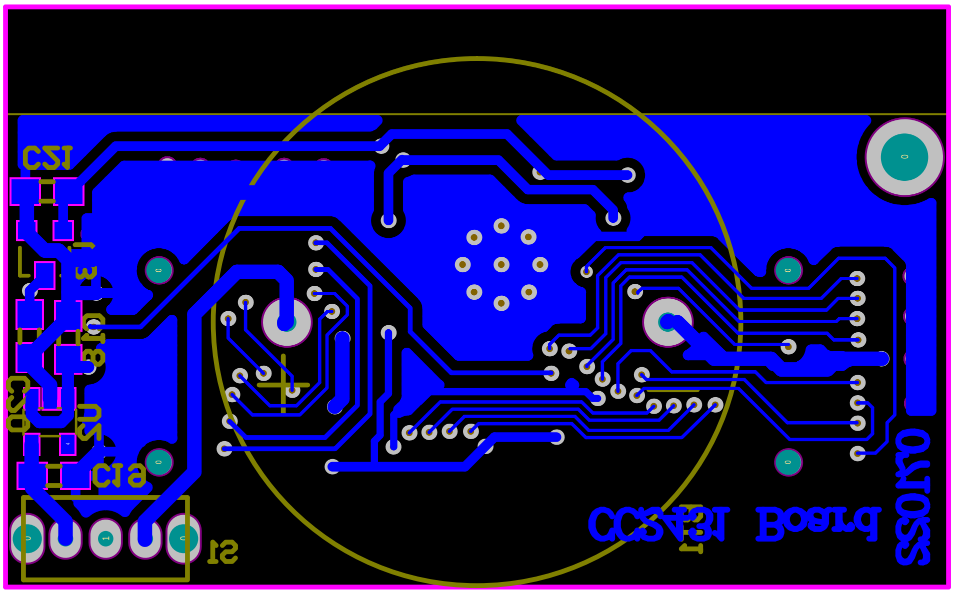
CC2430 wireless microcontroller module PCB



Multi layer

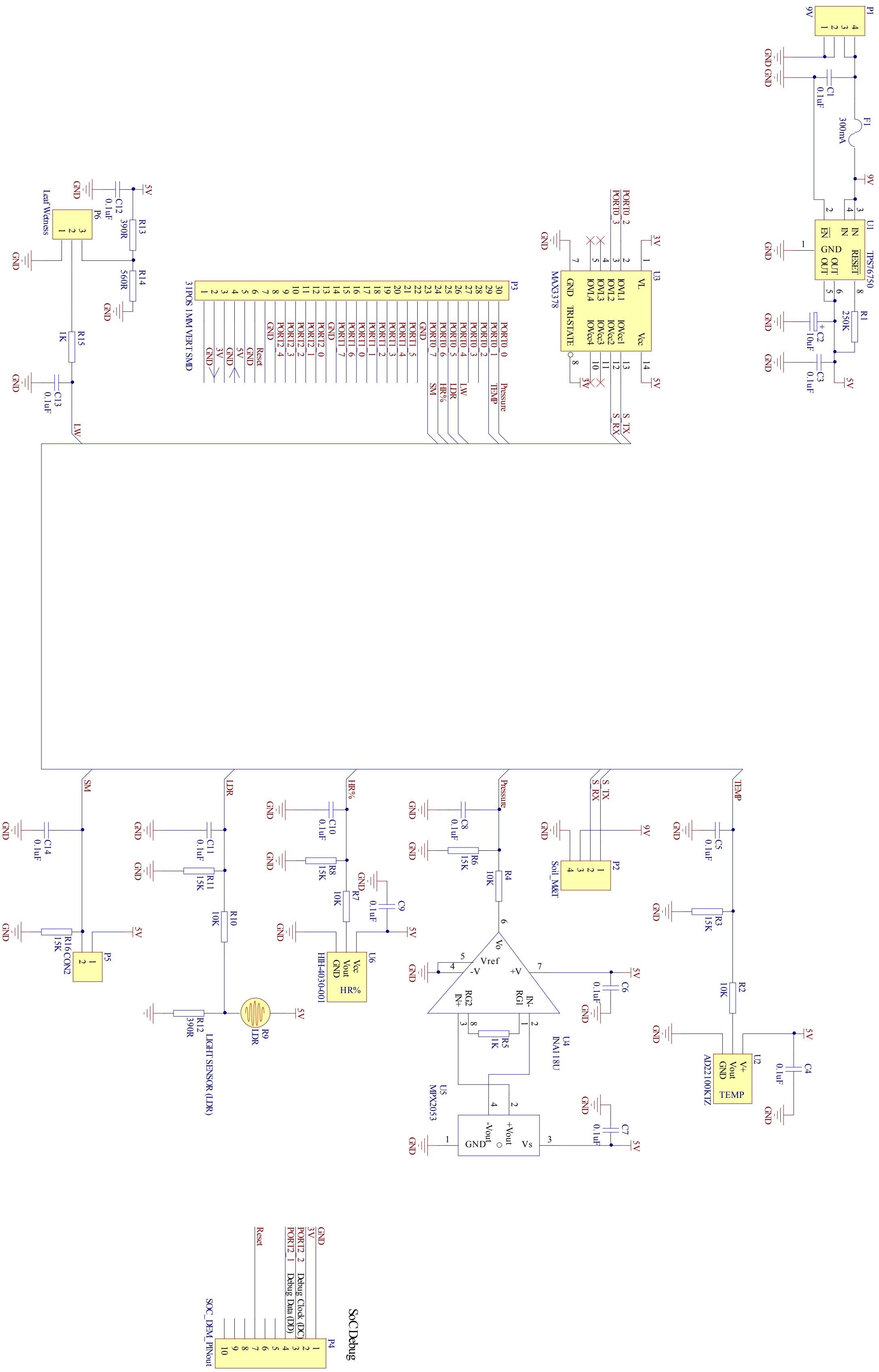


Top Layer

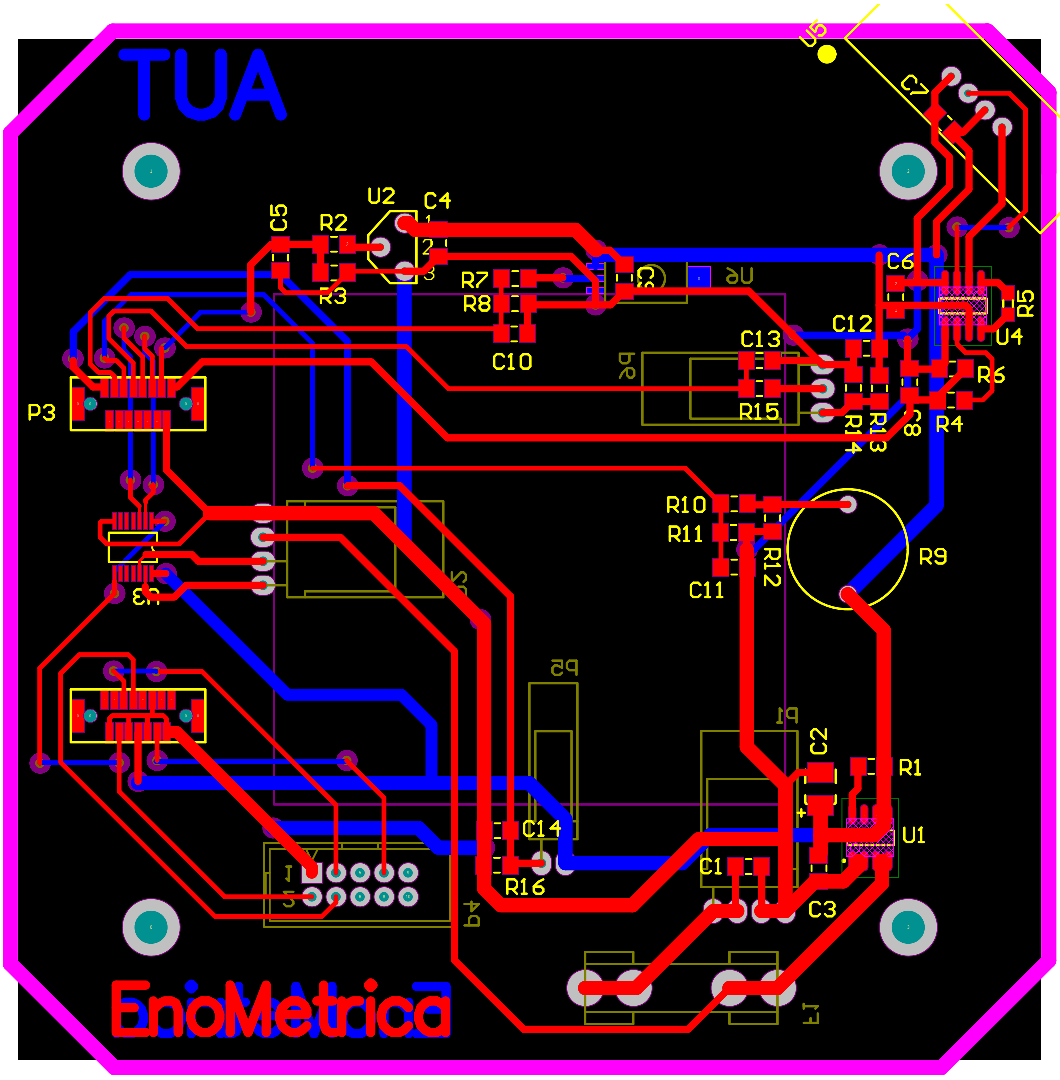


Bottom Layer

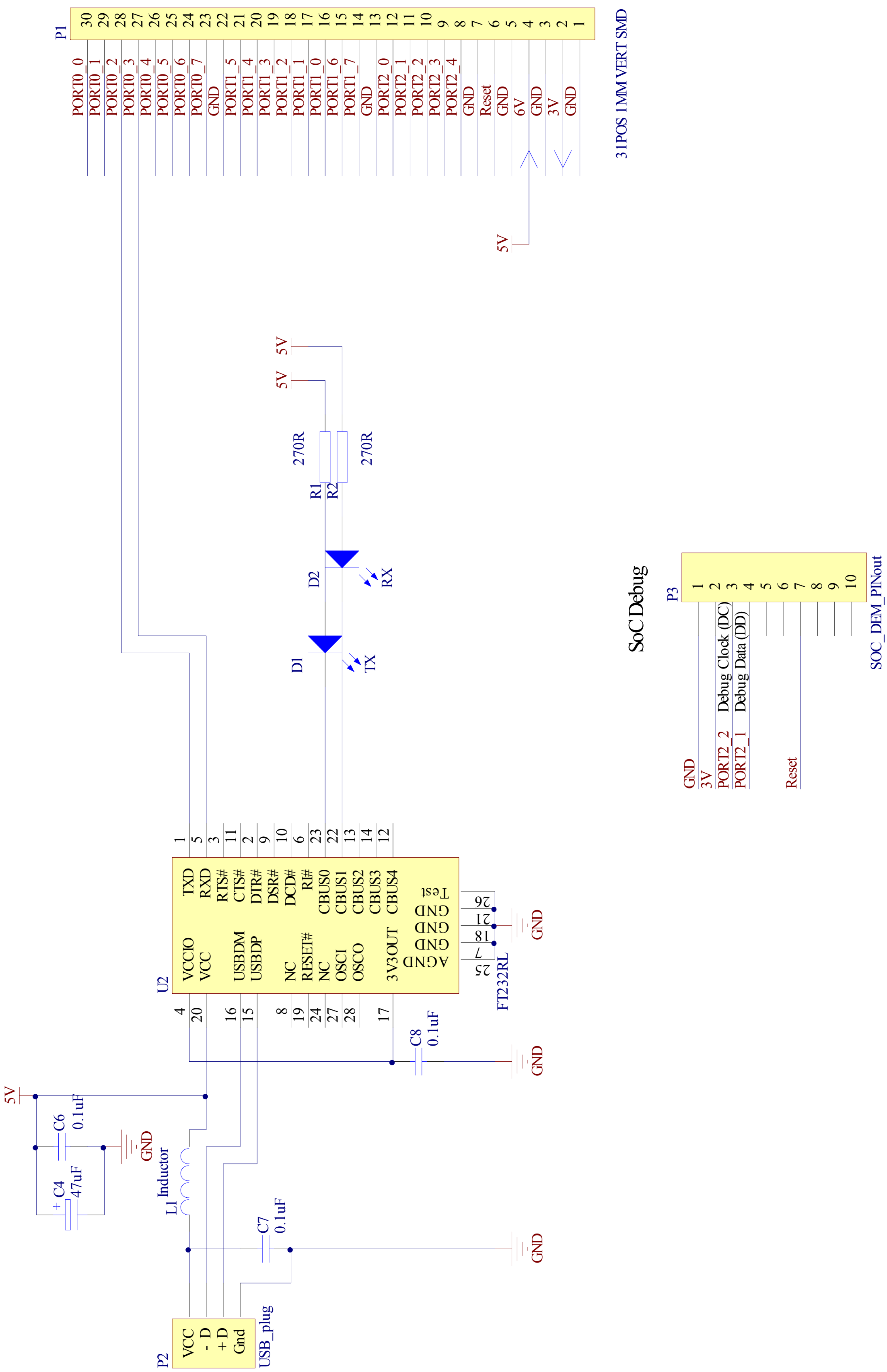
Sensor module schematics



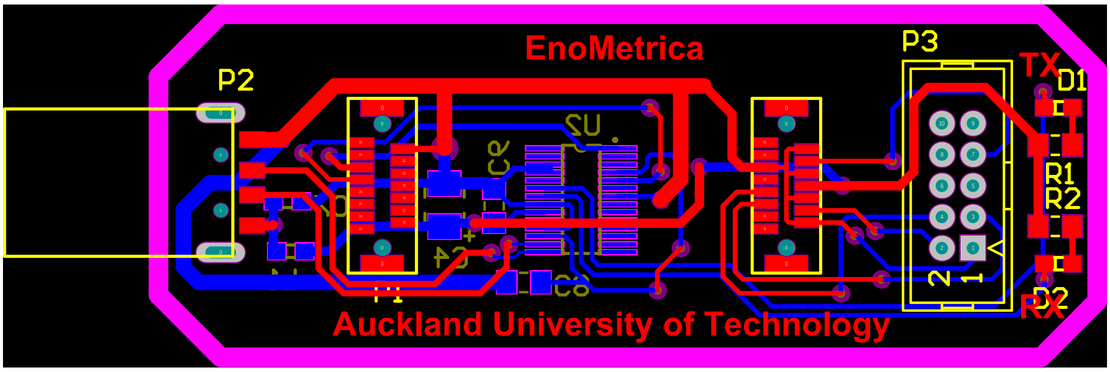
Sensor module PCB



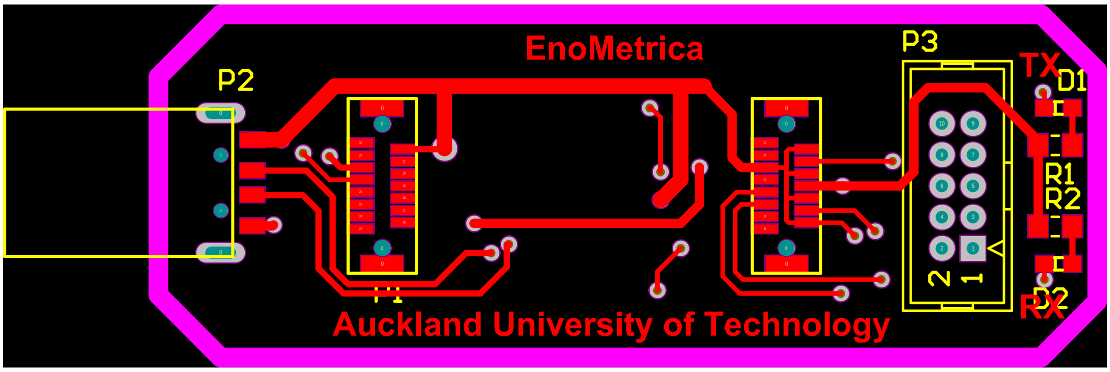
Coordinator module schematics



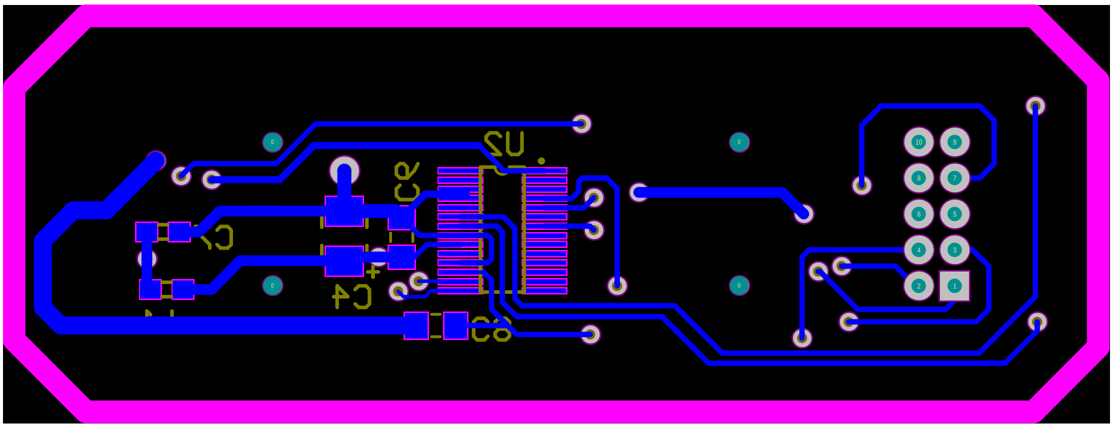
Coordinator module PCB



Multi Layer

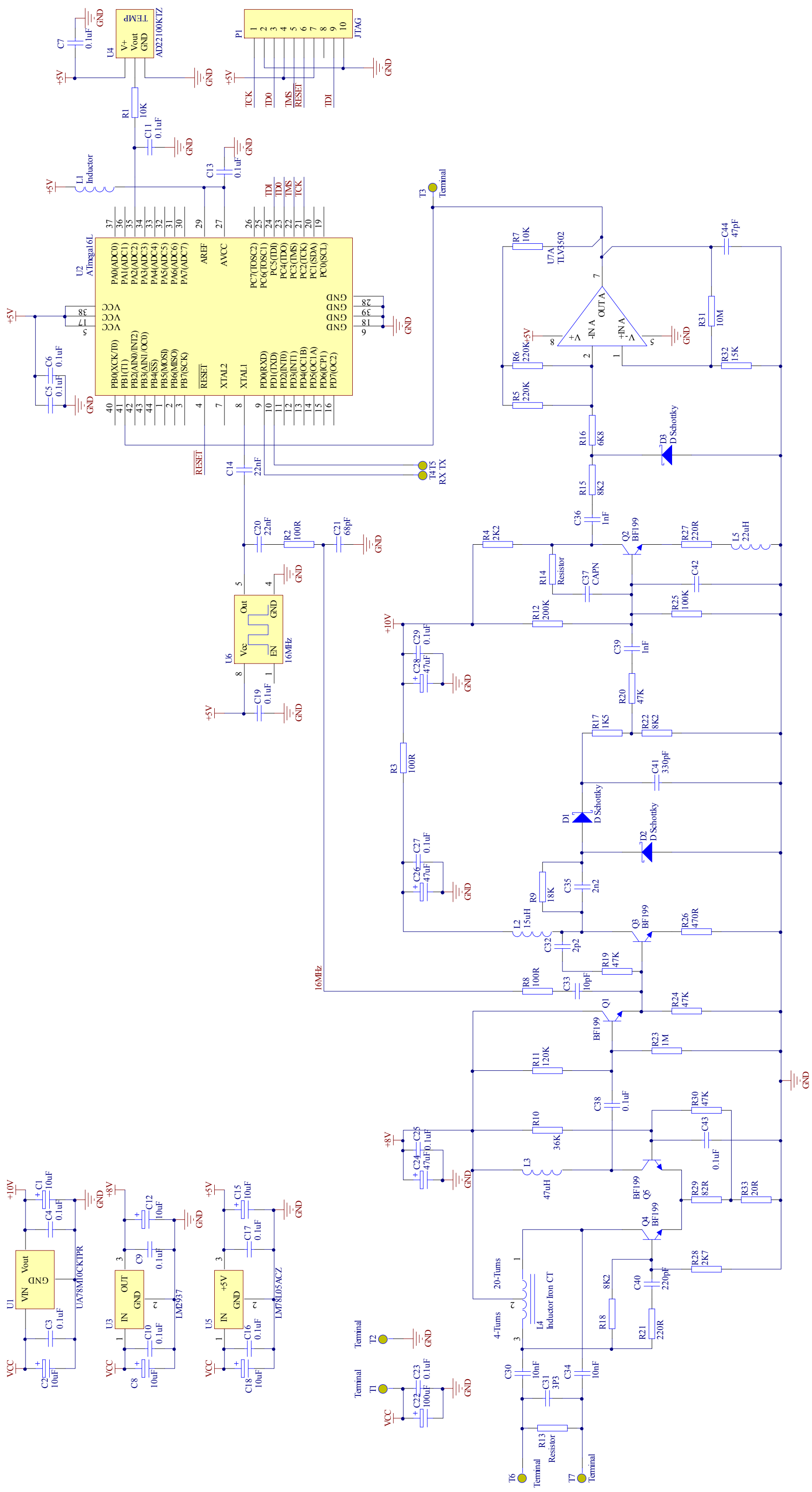


Top Layer

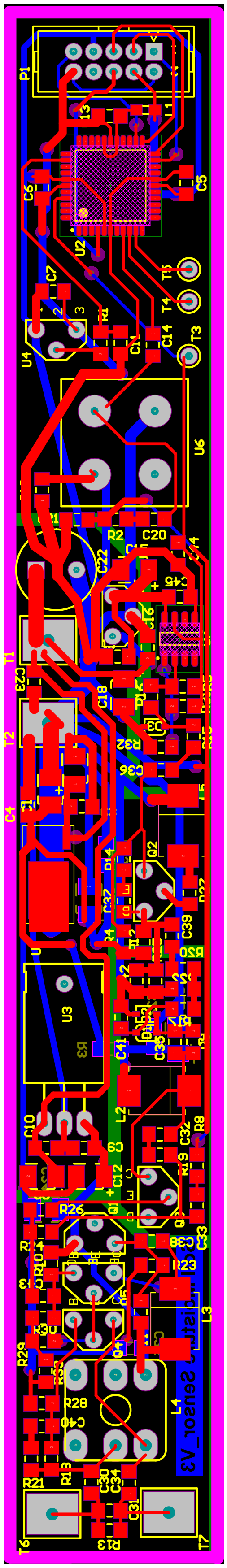

Bottom Layer

Appendix B – Soil Moisture Sensor Design

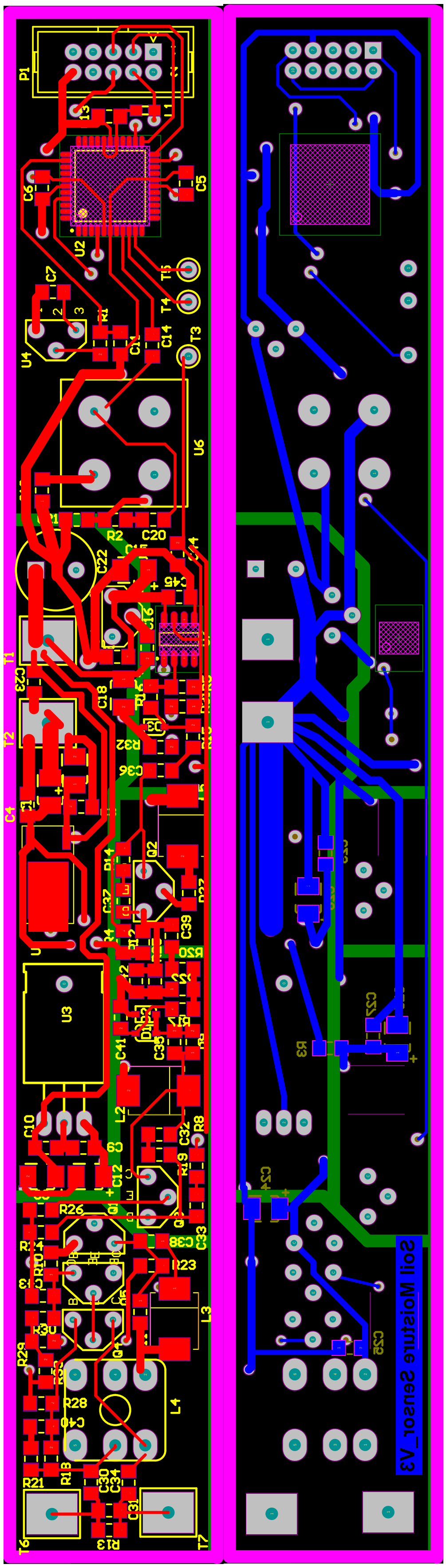
Soil Moisture senor schematics



Soil Moisture senor multilayer PCB



Soil Moisture senor top/bottom layer PCB



Appendix C – Software CD Directory Listing

This CD contains the firmware software files for coordinator node, router node and soil moisture sensor. The soft version of the circuit designs are also attached in a separate folder. The file locations are explained below. The software required to open these files are IAR complier, CodeVsion complier and Altium designer.

The CD is split into two sections, firm ware and hardware, which are described below.

Hardware Directory

CC2430 Wireless Sensor Module

Directory: \Hardware\CC2430 Wireless Sensor Module\Circuits\Version1

This directory contains the Altium schematics and PCB files for the CC2430 wireless sensor module.

Soil Moisture Sensor

Directory: \Hardware\Soil Moisture Sensor

This directory contains the Altium schematics and PCB files for soil moisture sensor.

Micro Climate Weather Station

Directory: \Hardware\Micro Climate Weather Station

This directory contains the Altium schematics and PCB files for the micro climate weather station unit.

ZigBee USB Coordinator Dongle

Directory: \Hardware\Zigbee USB Coordinator Dongle

This directory contains the Altium schematics and PCB files for the ZigBee USB coordinator dongle.

Software Directory

Soil Moisture Sensor Firmware

Directory: \Software\SM_Firm_Ware

This directory contains the firmware for the soil moisture sensor.

Coordinator Node Firmware

Directory: \Software\TI_Coordinator\Texas Instruments\ZStack-1.4.3-1.2.1\Projects\zstack\Samples\GenericApp\CC2430DB\CoordinatorDB

This directory contains the firmware for the coordinator Node.

Router Node Firmware

Directory: \Software\TI_Router\Texas Instruments\ZStack-1.4.3-1.2.1\Projects\zstack\Samples\GenericApp\CC2430DB\RouterDB

This directory contains the firmware for the router Node.