TALLINN UNIVERSITY OF TECHNOLOGY
School of Information Technologies

Khushboo Kumari, 184606IVEM

"An investigation of cost-effective soil moisture sensor for smart agriculture"

Master's thesis

Supervisor: Ants Koel
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Khushboo Kumari, 184606IVEM

“Kulutõhusate mullaniiskuse andurite uurimine kasutuseks nutikas põllumajanduses”

Magistritöö

Juhendaja: Ants Koel
PhD

Tallinn 2020

Author’s declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

Author: Khushboo Kumari

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Abstract

In agriculture, soil moisture sensing is critical for plant growth and to enhance crop productivity. Nowadays, technology has revolutionized agriculture applications. For instance, soil moisture sensors can be used to find the soil's current state: dry, wet, watery. The core aim of this thesis is to investigate the cost-effective soil moisture sensors by considering four sensors by investigating freely available COTS sensors from different manufactures and integrate the sensor with suitable communication technology for long-distance communication. A comparative analysis is performed for different commercial off-the-shelf soil moisture sensors in cost, accuracy, durability, and corrosion resistance. Secondly, feasible communication technology is investigated for long-range agricultural applications.

The sensors' accuracy is examined for three different soils, such as clay, loam, and silt soil, for three different temperatures, i.e., room temperature, 40^{o}C, and 50^{o}C. Soil preparation and maintenance of the environment are the most critical part of the experiment, which should be handled carefully.

Based on the experimental results, the author has found that capacitive sensors are better than resistive sensors due to their capability to avoid corrosion and provide better measurement readings. Capacitive V1.0 sensor is the most accurate, corrosion-resistant, and most durable among all the sensors. Capacitive V1.0 is costly than V1.2 but has more accuracy, while V1.2 is cheaper than V1.0 but has less accuracy. So, these sensors can be used based on the requirements,i.e., accuracy or cost. Moreover, the author has found that LoRa is a more feasible communication technology than NB-IoT for agricultural applications because of lower latency, low power consumption, long-range, and long battery life.

This thesis is written in English and is 84 pages long, including 5 chapters, 22 figures, and 14 tables.

Annotatsioon

Põllumajanduses on mulla niiskustundlikkus taimede kasvu ja põllukultuuride tootlikkuse suurendamise seisukohalt kriitilise tähtsusega. Tänapäeval on tehnoloogia muutnud põllumajanduse rakendusi. Näiteks mulla niiskuse andureid saab kasutada mulla praeguse seisundi leidmiseks: kuiv, märg, vesine. Selle lõputöö põhieesmärk on uurida kulutõhusaid mullaniiskuse andureid, võttes arvesse nelja andurit, uurides vabalt saadaval olevaid COTS-andureid erinevatelt tootjatelt ja integreerides anduri kaugsuhtluseks sobiva sidetehnoloogiaga. Erinevate kaubanduslike riiuliväliste mullaniiskuse andurite kohta viiakse läbi võrdlev analüüs kulude, täpsuse, vastupidavuse ja korrosioonikindluse osas. Teiseks uuritakse kaugpõllumajanduse rakenduste jaoks teostatavat sidetehnoloogiat.

Andurite täpsust uuritakse kolme erineva pinnase, näiteks savi-, savi- ja mudamulla puhul kolme erineva temperatuuri, st toatemperatuuri, 40 ° C ja 50 ° C korral. Pinnase ettevalmistamine ja keskkonna hooldamine on katse kõige kriitilisem osa, mida tuleks hoolikalt käsitleda.

Katsetulemuste põhjal on autor leidnud, et mahtuvuslikud andurid on paremad kui takistuslikud andurid, kuna neil on võimalus korrosiooni vältida ja pakkuda paremaid mõõtenäiteid. Mahtuvuslik V1.0 andur on kõigi andurite seas kõige täpsem, korrosioonikindel ja vastupidavam. Mahtuvuslik V1.0 on kulukas kui V1.2, kuid sellel on suurem täpsus, samas kui V1.2 on odavam kui V1.0, kuid selle täpsus on väiksem. Niisiis saab neid andureid kasutada vastavalt nõuetele, st täpsusele või maksumusele. Pealegi on autor leidnud, et LoRa on põllumajanduslikes rakendustes teostatavam sidetehnoloogia kui NB-IoT, kuna see on madalama latentsuse, väikese energiatarbimise, pika tööea ja pika aku kasutusaega tõttu.

See lõputöö on kirjutatud inglise keeles ja on 84 lehekülge pikk, sealhulgas 5 peatükki, 22 joonist ja 14 tabelit.

List of abbreviations and terms

PF	Precision Farming
IoT	Internet of Things
IoM	Internet of Meat
LPWAN	Low Power Wide Area Network
LoRa	Long Range
RFID	Radio Frequency Identification
NB-IoT	Narrowband Internet of Things
LTE-M	Long Term Evolution for Machines
SIDSS	Smart Irrigation Decision Support System
WSN	Wireless Sensor Network
SBD	Soil Bulk Density
TDR	Time Domain Reflectometry
FDR	Frequency Domain Reflectometry
TTN	The Things Network
RSSI	Received Signal Strength Indicator
COTS	Commercial Off-The-Shelf

Table of contents

List of figures

List of tables

1 Introduction

Technology has revolutionized each sphere of life. Smart agriculture or smart farming is also an example of this revolution. This is the era of “smart things” where things are intelligent and clever enough to make their own decisions without humans' involvement. Researchers are working globally to contribute value to agriculture such as monitoring of plants, smart irrigation system, soil moisture monitoring [1]. Agriculture is an inevitable part of human survival because it is the major source of food. According to the United Nations, the World population is estimated to reach more than 9.7 billion by 2050. Hence, double food consumption should be provided, particularly in developing countries. Food for all is one of the fundamental difficulties of the 21st century. Not only production but lowering down its side effect on climate change is also a vital challenge [2].

A sustainable system should be provided, where climate change could not affect the productivity of the plants. Water is the basic need in agriculture and the water demand, or the volume of water needed to sustain a healthy plant, can't generally be fulfilled by rainfall alone. When rainfall occurs, soil cannot store all the water from it. For farming, timely and fair irrigation is completely is very important for crop production. Additional water necessity for crops can be approximated as the potential difference between moisture deficit through evapotranspiration and moisture entering through irrigation or rainfall. Whereas, scarcity of water can lead to droughts and over-irrigation can cause damage to the root of crops. Apart from the food, crops like cotton and rubber play a significant part in the economy [3]. Moreover, soil acts as an important part of earthly water dynamics by maintaining precipitation on the ground. Mechanical characteristics of the soil like texture, compatibility, breaking, swelling, shrinkage, and density are reliant on the content of soil moisture. They all have a significant part to play in plant growth. Precision farming is required in this case. Precision farming gives a platform where farmers can produce a quality of crops at a lower cost. This is possible to achieve through the usage of smart agriculture.

Smart agriculture can be defined as a process where various sensors are integrated with communication technologies to monitor the changes in the environment due to various external factors, and collected data is optimized to make a smart decision. Steps involved in an intelligent agriculture system are as follows: sense the agriculture parameters such as soil moisture, temperature, etc., identification of target location and gathering of data, data transfer from the field to the control station, and finally make the decision based on various factors such as domain knowledge, actuation, and control, local data, etc. [1]. Smart agriculture systems can be implemented using smart devices and the Internet of Things (IoT) services. Visible advantages and dominance of the Internet can be noticed across the globe. This has enabled the development of the IoT. Low-power and affordable microprocessors have been developed and taken into use. It facilitates to produce robust, cost-effective, and low-power devices that can fulfill the needs of precision agriculture. The process is accelerating because of its pervasive, highly interoperable, and open nature. It is also estimated that by 2020, 25 billion devices would be associate remotely, as shown in Figure 1 [4].

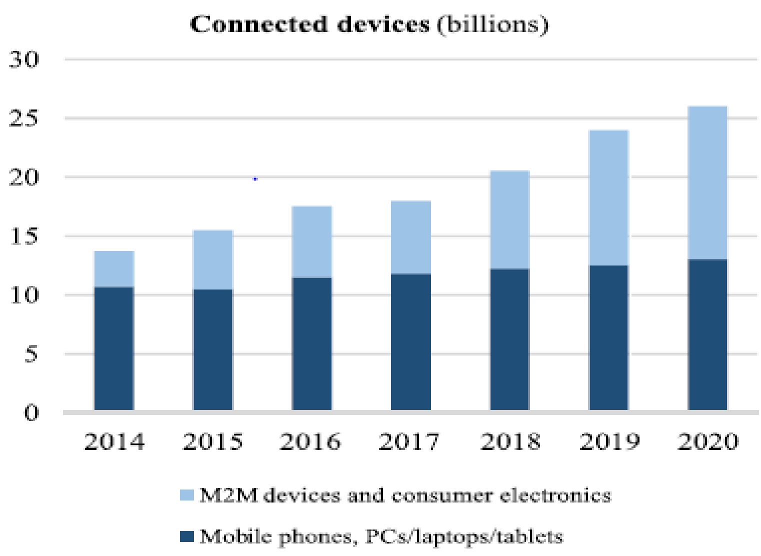

Figure 1.1. Increase in IoT devices [4]

According to [5], in the coming years, IoT will become the Internet of Meat (IoM) because the technology will be injected into the body and connected and accessed by wireless communication technologies. According to Gartner Hype Cycle figure 2. IoT is one of the emerging technologies in the coming 2 to 5 years.

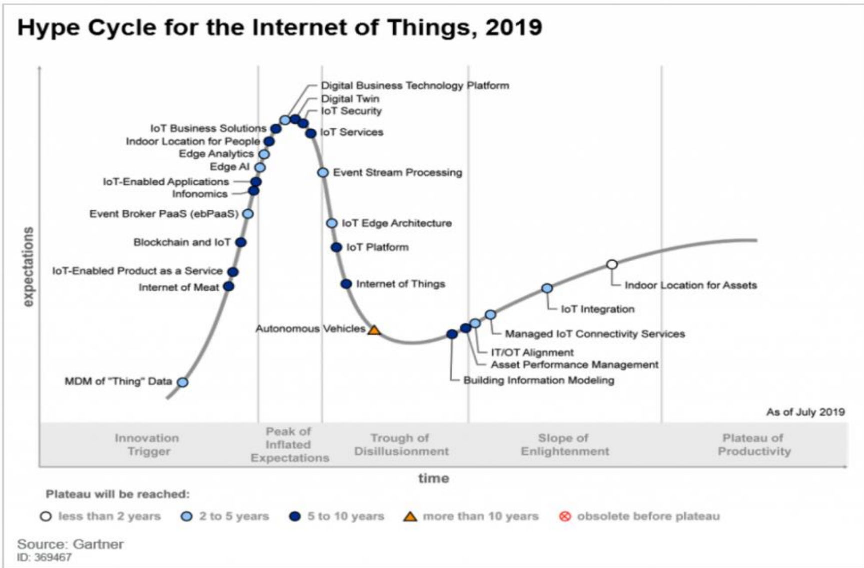

Figure 1.2. Hypercycle for the Internet of Things [5]

Smart agriculture is relying on the integration of smart devices, such as sensors and communication technologies. For precision farming (PF), the analysis of the field parameters is important. Farmers require smart technology that can help them to maintain the quality of crops [3]. PF needs a frequent visit to the land. Regularity is very important for the optimal production of crops. The development of Low Power Wide Area Network (LPWAN) technologies solves this problem of frequent visits to agricultural land because LPWAN communication technologies support a wide area of communication with low-power consumption; PF will help to irrigate our agricultural land timely and adequately. The deficiency of affordable solutions gives critical agricultural distress, and it especially hits poor farmers. The worth of money of the sensors is shown in their accuracy and precision. Hence, proposing affordable soil moisture sensors with high accuracy and precision is important for all groups of farmers.

LPWAN first appeared to market in 2013. It is very useful for IoT devices because IoT devices need to send a small amount of data only. LPWAN covers long distances at the constrain of the low data rate. LPWAN provides us low power, wide-area, and long battery life communication, which is perfect for IoT devices. These networks can gather data from a large area and can upload it to the system for analysis. Few wireless networks are effective for data transmission in the sensor network.

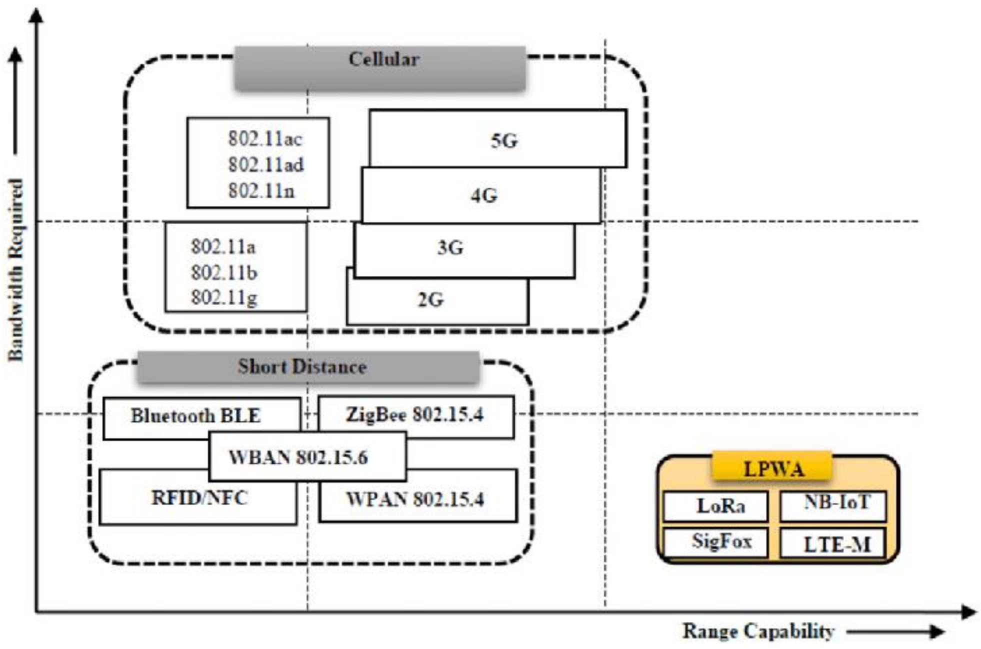

Figure 1.3. Bandwidth vs. range capacity of short distance, cellular, and LPWAN [6]

Figure 3 illustrates the bandwidth vs. a range of wireless communication technology. It is mentioned that LPWAN covers longer distances than all the other technologies. Low power networks are ZigBee, Bluetooth, Radio Frequency Identification (RFID), Long Term Evolution for Machines (LTE-M), Sigfox, Narrowband IoT (NB-IoT), and Long Range (LoRa). In this, some are licensed, and some are unlicensed [4]. Zigbee, Bluetooth, RFID are not useful for our work because they don't cover long distances like Sigfox, NB-IoT, and Lora.

1.1 Applications of IoT in smart agriculture

Agriculture IoT has numerous applications such as crop monitoring, water management, soil monitoring sensor, machines for routine operations, etc. [7], which is shown in Figure 4. Some of these applications are briefly explained here.

1. **Water Management**

   In the contemporary era, scarcity of water is a potential global issue. So, the smart irrigation system is a contemporary need to control the excess water usage that also affects crop quality and production. Novel technology is mentioned by [8], which is known as an "automatic smart irrigation decision support system (SIDSS)" which helps in effective water management and irrigation of the crop fields by making a smart decision according to climatic conditions, characteristics of soil and weather prediction etc.

Figure 1.4. Applications of smart agriculture system [7]

2. **Monitoring of livestock**

With the help of smart devices, it is possible for farmers to collect information about the schedule of the feeding, location, and health condition of the cattle. For instance, if one animal is sick, then it can be found by continuous monitoring of the herd, and other animals can be saved before contamination [9].

3. **Monitoring of climate conditions**

Climatic conditions are responsible for plant growth or crop production. So, it is essential to monitor the rough changes in climatic conditions such as temperature and moisture. The use of the temperature and moisture sensors to get the real-time instantaneous values of these factors helps to manage the adequate amount of water, which eventually helps to increase the efficiency of the farm [10].

4. **Soil moisture monitoring**

   Monitoring of soil moisture is very essential to maintain the soil profile i.e. is the quality of soil good for the plants or for identifying diseases which may harm the crop production. Soil sensors are used to measure the electrical conductivity, moisture, temperature, nutrients and sense other soil properties. This collected information is used to estimate the soil profile and based on that, the amount of fertilizers is determined for the farm [9].

1.2 Motivation to study soil moisture

Farming has been around us for thousands of years, which supports mankind to grow and create stable settlements for their better wellbeing. The latest investigation on climate change shows that the conditions might get worse. As a result, people will face dry seasons more rapidly [11]. We all know that various factors need to be considered for precision farming. Factors like temperature, moisture, rain and several others influencing the optimal growth of the plant. Soil moisture measurement techniques are in the market for many decades. Soil moisture sensors that give high accuracy are very expensive and still far away from the majority of farmer's daily uses. There exist low-cost soil moisture sensors in the market as well. Due to their very slow and inaccurate measurement, they didn’t get popularity [12].

Therefore, the main objective of this thesis work is to evaluate the soil moisture sensors which should be accurate, reliable, precise, low-cost and durable in the way that these can be used for precision agriculture. Soil moisture sensor that will be having accuracy, low-cost and low-power consumption can be used broadly, even in developing countries. Soil moisture data must be gathered for the analysis purpose so that when to irrigate or plants for optimal production to be decided. This can be done with the help of LPWAN technologies. As NB-IoT and LoRa are more suitable for the long-range capabilities, these technologies have been selected for evaluation to find which technology suits better for the low-cost agricultural IoT scenario.

1.3 Problem Statement

The problem statement of this thesis work is to find a soil moisture sensor that keeps the moisture of the soil between optimal levels that plays an essential role in plant growth. Sensors previously available on the market have been too costly for many farmers in emerging countries. Affordable moisture measuring equipment can help in mitigating this problem and farmers can do precision farming with the help of the latest technologies. Less amount of work has been done in the practical implementation of the affordable soil moisture sensors.

Given the above, the research statement of this thesis work is as follows:

- ❖ **Comparative analysis of different COTS soil moisture sensors in terms of cost, accuracy, durability, corrosion resistance.**
- ❖ **Comparative analysis of LoRa and NB-IoT technology to examine the feasible communication technology for the given scenario.**

1.4 The approach followed to achieve the goal

The primary objective of this thesis is to analyze various soil moisture sensor to achieve the following results:

- Find COTS soil moisture sensors available on the market and select cost-effective sensors for further comparison;
- Test the accuracy, precision, and low power of the sensors;
- Select a networking technology solution for data acquisition;
- Integrate the measurement technology with networking technology;
- Sends and receives the soil moisture data over a long-range;
- Check the operation of sensor network indoor and outdoor as well;

1.5 Significance of work

Over many years, ample techniques have been analyzed and used for soil moisture measurement. This measurement allows monitoring of agricultural land without visiting frequently. Due to modern measurement techniques, low-cost sensors like capacitive and resistive for moisture measurement. Dielectric measurement technique or as more recent measurement technique is becoming more and more popular for low-cost and excellent accuracy. The benefits of wireless sensor networks (WSN) will be used for low-power and long-distance communication. The novelty of this thesis is that it will investigate the cost-effective soil moisture sensors by considering four sensors by investigating freely available COTS sensors from different manufactures and integrate the sensor with suitable communication technology for long-distance communication.

This thesis report is consisting of six chapters. Chapter 1 covers a general introduction, motivation, problem statement. Chapter 2 focuses on the literature review and methodology. Chapter 3 provides a detailed description of devices, hardware, and software requirements to execute the project. Chapter 4 covers the implementation and discusses the results and findings. Chapter 5 presents the conclusion and future scope of the work. This thesis ends with references and appendices.

2 Literature Review

This chapter represents the background of various soil moisture sensors, which gives a deep understanding of the literature behind the investigation of low-cost and accurate soil moisture sensors.

2.1 Soil Moisture and its type

Soil moisture is a key factor which has a strong impact on nutrients of soil. It is very essential to consider this factor, for instance, in low rainfall region, fertilizer rates should be chosen according to the soil moisture level. Fertilizers usage according to soil moisture levels provides a good economic return [13]. Moreover, according to [14], soil moisture is a pivotal state variable which helps to understand the dynamics of earth system as movement of water through different soils and landscape is different. So, it is every important to understand the pattern of soil moisture. Soil moisture varies because of several reasons like temperature, landscape position, soil structure and composition and man-made structure on the soil [4]. Every agriculture field has its own characteristics that totally depend on its soil types which gives us ideas about the quality and quantity of production.

Soil moisture (θ) is expressed in Equation 2.1 as the ratio of the total volume of soil that is wet where V_w is the wet volume and V_T is the volume of the soil both measured in cm3.

$$\theta = V_w / V_T \tag{2.1}$$

Soil moisture is of three types gravitational, capillary and hygroscopic moistures [15].

2.1.1 Gravitational moisture

This moisture moves through the soil freely because of the gravity. It generally traps into the macropores of the soil. It moves rapidly in the soil and stays in the soil for 2-3 days after irrigation or rainfall [15].

2.1.2 Capillary moisture

This moisture generally traps into the micropores of the soil because of the coherence and adhesion. This moisture is responsible for every physical-chemical- mineralogical-biological communication between the clay and the outer world [15].

2.1.3 Hygroscopic moisture

This moisture generally presents on the surface of the soil. And this soil moisture is very hard to remove from the soil due to the adhesiveness against the gravitational force. This kind of moisture generally presents in the clayey soil in comparison to the sand because sand has a high surface area [16].

2.2 Soil moisture measurement techniques

Soil moisture techniques can be divided into two types such as direct methods and indirect methods which is shown on Figure 2.1. Direct methods include gravimetric or thermo gravimetric techniques whereas indirect methods include tensiometric, electrical or electromagnetic, radiation, thermal and remote sensing methods.

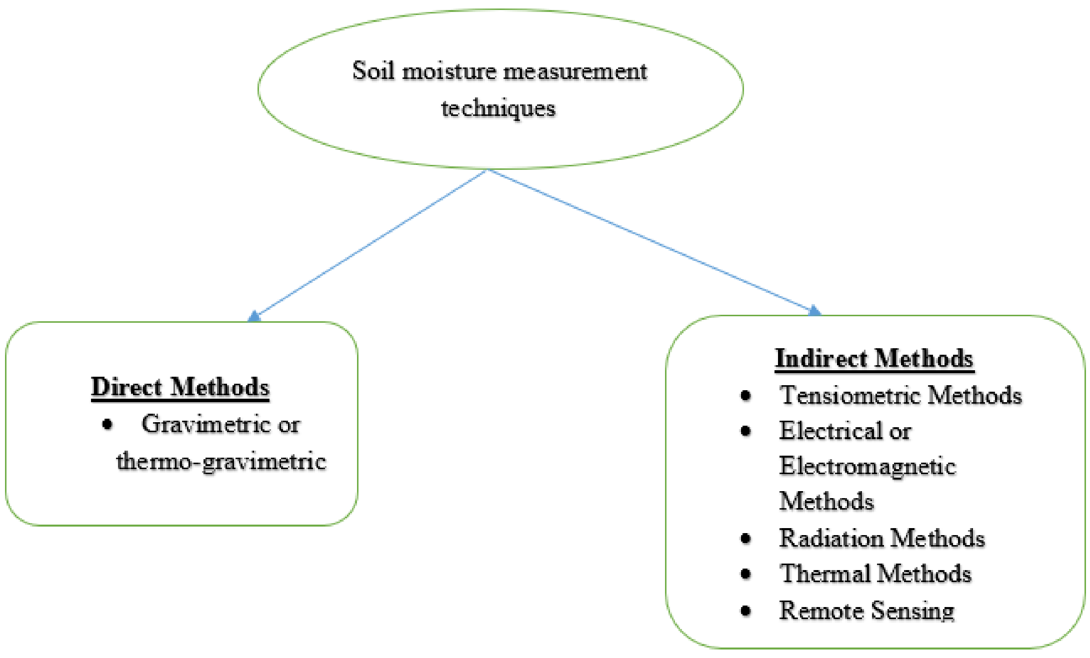

Figure 2.1. Soil moisture measurement techniques

2.3 Direct moisture measurement techniques

Direct moisture analysis techniques extract soil moisture by drying it inside the oven or it includes some chemical reaction process like calcium carbide technique and thermo-gravimetric process [20].

2.3.1 Thermo-gravimetric technique

This is the oldest and most popular soil moisture measurement technique. It is based on the principle of weighing of the soil before and after the oven drying. We keep wet soil samples inside the oven for 24 hours at 105 C. But in case of organic soil moisture temperature is always in between 50-70 C. This process is very much accurate for finding soil moisture irrespective of soil types and salinity [21]. There is no need for any specific calibration. The moisture in the soil can be computed by using the following formula:

$$\%\ \text{Moisture measurement} = \frac{\text{wt of wet soil} - \text{wt of dry soil}}{\text{wt of dry soil}} * 100 \qquad (2.2)$$

Volumetric water measurement can measure by knowing soil bulk density (SBD).

$$\%\ \text{Volumetric water content} = \frac{\text{wt of wet soil} - \text{wt of dry soil}}{\text{wt of dry soil}} * 100 * \text{BD} \qquad (2.3)$$

Where, BD denoted bulk density.

But there are few demerits of it which inhibits the use technique are:

- This method is time-consuming;
- Hard to measure the different depth of moisture content and;
- The soil used for oven drying cannot be used again for measurement because drying changes the soil structure.

2.3.2 Calcium carbide technique

It is one of the fastest methods to find soil moisture content. It is also called as a speedy soil moisture technique. This technique uses chemical reaction for determining the soil moisture. In this, calcium carbide will diffuse with moisture available in the soil and produce acetylene gas. Equation 2.4 shows this chemical reaction [22]:

$$CaC_2 + 2H_2O = Ca(OH)_2 + C_2H_2 \quad (2.4)$$

2.4 Indirect/Modern moisture measurement techniques

Modern technique has various methods to measure soil moisture.

2.4.1 Radiation technique

Radiation technique can be divided into neutron scattering and gamma-ray attenuation technique which are elaborated in the next sections.

- **Neutron Scattering**

The neutron moisture measurement technique scatters neutrons. It is extensively used for measuring volumetric soil moisture. Its response time is 1-2 min approximately which makes it fast. Figure 2.2 reflects the working of neutron probe. This measurement technique helps us to measure a large surface area. In this, neutrons particles hit the hydrogen atom which is present in the soil. As it emits neutrons, therefore we need to have training about it.

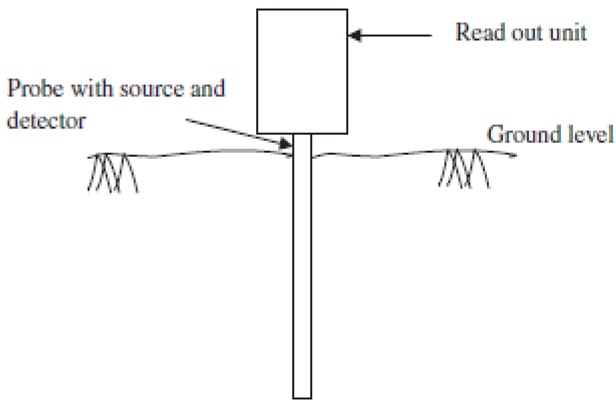

Figure 2.2. Neutron probe [16]

On the other hand, the major disadvantages [16] are:

- Expensive
- Radiation hazard
- It must calibrate for different soil types.

- The resolution of depth is still doubtful.
- The analysis is somewhat reliant on physical and chemical soil characteristics.
- We can variations in measurements because of soil density.

Advantages:

- It is a non-destructive way of measurement.
- It can measure water in any phase.
- Robust and precise
- Not affected by salinity or air gaps

- **Gamma-ray attenuation technique**

It is a radioactive technique, and it can determine the moisture from the depth 25 mm or even less than that with a great resolution. Scattering and absorption of gamma-ray take place in this technique. The absorption of beam energy detects moisture content. It is faster than the neutron probe because its response time is less than a minute. However, it is more harmful than the neutron probe as well as it is costlier than the neutron probe [16].

Disadvantages:

- It is costly and complicated to use.
- Failure in situ water condition during freezing, thawing or iced.
- Huge alteration in moisture content can happen in highly layered soil

Advantages:

- Temporary soil moisture variations can be quickly observed
- Non-destructive
- The sampling period is comparatively quick around 10 seconds

2.4.2 Remote Sensing Technique

Recently, remote sensing methods have been applied to measure soil moisture. Evaluation of moisture by remote sensing techniques renders only exterior knowledge and is inadequate to witness the whole soil [16]. Moreover, field analysis gives relevant data about both surface and subsurface moisture of the soil [20].

Some of its major drawbacks are:

- Quite complicated material commonly including satellites
- A highly valuable approach needing the usage of satellite arrangements in most events.

Merits:

- Quick method
- No need of calibrations
- the health risk is not involved with this technique.

2.4.3 Thermal dissipation technique

A thermal dissipation sensor is made of porous ceramic material. It has a tiny heater inside it which is placed inside the soil and a temperature sensor is kept at the sensor with the help of a cable. When we apply voltage to the heater than heat dissipation is measured. This heat radiation is linked to soil moisture. But this device needs to calibration and it is costly [16].

2.4.4 Electromagnetic techniques

Electromagnetic (EM) techniques involve methods that rely on the impact of moisture on the electrical properties of soil. The resistivity of soil depends on moisture content therefore it can help for the foundation of moisture sensor. All EM techniques depend on the dielectric permittivity. Because there is a big difference in the dielectric constant of soil and water. The dielectric constant of dry soil is between 2 to 5 and for water is approximately 81. Electrical permittivity cannot get altered by the effect of temperature changes. Due to this EM sensor, like Time domain reflectometry and capacitance techniques are a very common and accurate method for moisture measurement [23]. This technique can be divided into Time Domain Reflectometry (TDR) technique and capacitive technique.

- **TDR technique**

TDR technique is one of the widely used instruments for soil moisture measurement. It suggests measuring the dispersion of electromagnetic waves (EMW). This technique is fast, nearly free from soil type, non-destructive, befitted for surface and profile measurements. Thus, if the soil is wetted the dielectric constant (K) is large and the travel time of the EMW waveguides will be maximum. If the soil is drained the travel time of waveguides will be small. TDR provides the dielectric constant, K of soil which is analytically associated with the volumetric water content (θ) it is stated in given below Equation 2.5,

$$K = [c.t/2L] \tag{2.5}$$

In the above equation, c is the velocity of light, t is the transient time for EM wave and L is the length of the probe.

$$\theta = 4.3 * 10^{-6}(\mathrm{K}^3) - 5.3 * 10^{-2} - 5.5 * 10^{-4}\ (\mathrm{K}^2) + 4.3 * 10^{-6}(\mathrm{K}^3) \tag{2.6}$$

Here, K is the measured dielectric constant of soil. Above equation 2. is Topp's equation for measuring volumetric water content (VWC). Topp's noticed that soil composition like structure, moisture level, temperature, salt, and measured frequency influenced the electrical response of soil [].

Working principle of TDR

It measured the dielectric permittivity (K) of soil by evaluating the delay between the incident and the reflected EMW. EMW propagates along with the probes which are inserted in the soil. The large variation within the dielectric constant of the water and soil makes the travel time of the pulse depends on the volumetric moisture content (θ) [16]. Figure 2.3 depicts the layout of soil moisture measurement using TDR technique.

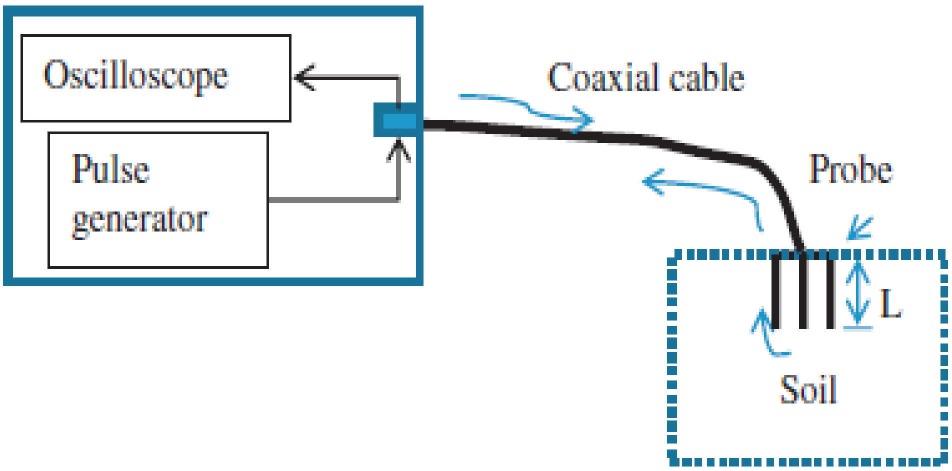

Figure 2.3. The layout of soil moisture measurement using the TDR [16]

Advantages:

- Accurate
- Calibration is usually not required for different soil types
- Minimum soil disruption
- Comparatively insensitive to regular salinity levels
- It can accommodate synchronous measures of soil electrical conductivity as well

Disadvantages:

- Comparatively high-priced devices due to complicated electronics
- Comparably little sensing volume (3.05 cm) range about the length of waveguides.
- Lack of reflection in highly saline soil.

Capacitive technique

The capacitance-based methods have an oscillating circuit and a sensing component that is installed in the soil. Here, frequency relies on the dielectric constant of soil. Measurement of the charge time of the capacitor is required for finding the dielectric constant. It generally consists of two electrodes which produce a capacitor by the soil as the dielectric. Variations in soil moisture content are identified by the variances happening in the operating frequency (10–150 MHz). The working principle of the Capacitive sensor and TDR is similar. But capacitive sensor uses swept frequency for getting data.

Advantages:

- Accurate after soil specific calibration
- Can read in high salinity levels, where TDR fails
- Better resolution than TDR (avoids the noise that is implied in the waveform analysis performed by TDRs)
- Flexibility in probe design (more than TDR)
- Devices are relatively inexpensive compared to TDR due to the use of low-frequency standard circuitry.

Disadvantages:

- It is extremely critical for reliable measurements to have good contact between the sensor (or tube) and soil.
- Careful installation is necessary to avoid air gaps
- Needs soil specific calibration.

Resistive technique

As soil moisture content increases, soil resistivity decreases. The quantification of soil resistivity can be done by measuring either the resistivity between electrodes in soil or the resistivity of material in equilibrium. When the soil's water content is high, the soil has a stronger electrical conductivity, resulting in lower resistance levels that indicate a high soil moisture. When the water content in the soil is low, the soil has poorer electrical conductivity, hence resulting in a higher resistance which indicates as low soil moisture

Advantages:

- A simple method of measurement.
- It delivers the results immediately.
- Very low in cost.

Disadvantages:

- Sensors provide less accuracy in sandy soils due to large particles.
- Sensors are required to be calibrated for each soil type.

However, Capacitive sensors are relatively affordable, accurate, and easily work on any soil type suitable for this thesis work.

3 Materials and Methods

In Chapter 2, background study of the soil moisture sensors is presented clearly. This chapter 3 consists of description of materials/products which are used for experimentation to find the cost-effective with defined figure of merits such as accuracy and precision. Here, four soil moisture sensors from different manufacturers are used for the practical implementation. The specifications are described in this chapter. Moreover, communication technology is also an inevitable part of this thesis, as it helps to communicate with sensor to transmit and receive the information which is also discussed in this Chapter 3.

3.1 Capacitive Soil Moisture Sensors

As the name indicates, soil moisture level is measured using capacitive sensing. Capacitive sensing technique is described under section 2.5.4. The popularity of this sensor is due to its long service life because it has ability of corrosion prevention. In addition, this sensor provides operating range of 3.5V to 5.5V as an on-board voltage regulator is available which makes it more usable. It is also compatible with Raspberry Pi and low-voltage Microcontroller Units (MCU) [24]. Two capacitive sensors named as Capacitive Soil Moisture Sensor V1.0 and Capacitive Soil Moisture Sensor V1.2 are used for the implementation in this thesis.

3.1.1 Capacitive Soil Moisture Sensor V1.0

This soil moisture sensor can be directly connected to Gravity I/O expansion shield because it is compatible with 3-pin Gravity interface.

Table 3.1. Specification of Capacitive Soil Moisture Sensor V1.0 [25]

Feature	**Value**
Operating Range	3.3 – 5.5 VDC
Output Voltage	0 – 3.0 VDC
Operating Current	5mA
Interface	PH2.0 – 3P
Dimensions	3.86 x 0.905 inches (L x W)
Weight	15g
Manufacturer	DFRobot
Price	$ 1.50

Figure 3.1. Capacitive Soil Moisture Sensor V1.0 [25]

3.1.2 Capacitive Soil Moisture Sensor V1.2

The manufacturer of this product is Paialu and this sensor supports 3-pin Gravity Sensor interface.

Table 3.2. Specification of Capacitive Soil Moisture Sensor V1.2 [26]

Feature	Value
Operating Range	3.3 – 5.5 V
Output Voltage	0 – 3.0 V
Interface	PH2.0 – 3P
Dimensions	99 x 16 mm/ 3.9 x 0.63”
Weight	40 g
Manufacturer	Paialu
Price	$ 0.72

Figure 3.2. Capacitive Soil Moisture Sensor V1.2 [26]

3.2 Resistive Soil Moisture Sensors

These sensors are used to measure the volumetric content of water using two probes. The current passes through these two probes to measure the moisture value by measuring its resistance. If there is more water, the soil is able to conduct more electricity that means the value of resistance is less. Therefore, the moisture level is higher. On the other hand, when there is less water, the soil conducts less electricity that means the value of resistance is more. Therefore, the moisture level is lower. Hence, dry soil is poor conductor of electricity [24]. Two resistive soil moisture sensors named as SEN0114 and resistive moisture sensor V2 are used for the implementation in this thesis.

3.2.1 SEN0114 (Resistive soil moisture sensor)

The specification of the resistive soil moisture sensor (SEN0114) is given in Table 3.3. As mentioned before, the working principle of this sensor based on soil resistivity measurement. It is useful to monitor the water requirement for the plants in gardens.

Table 3.3. Specification of Resistive Soil Moisture Sensor (SEN0114) [27]

Feature	**Value**
Power Supply	3.3 V or 5 V
Output Voltage Signal	0 – 4.2 V
Current	35 mA
Pin Definition	Analog output (Blue wire) Power (Red wire) GND (Black wire)
Size	60 x 20x 5 mm
Value Range	0 – 500 (In water) 500 - 750 (Humid soil) > 750 (dry soil)

Manufacturer	AZDelivery
Price	$ 1.59

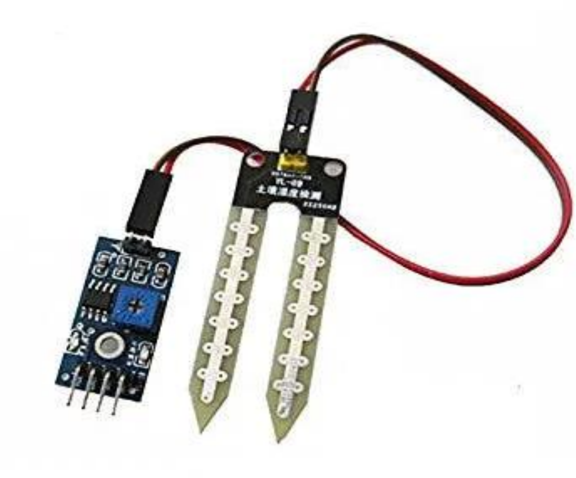

Figure 3.3. Resistive soil moisture sensor (SEN0114) [24]

3.2.2 Grove - Resistive soil moisture sensor

The specification of the Grove- Resistive soil moisture sensor is given in Table 3.4. This sensor is cost-effective and easy to use. Moreover, it is compatible with Grove interface. It can be used for moisture sensing, botanical gardening, and measurement of consistency [28].

Table 3.4. Specification of Grove - Resistive Soil Moisture Sensor [28]

Feature	**Value**
Power Supply	3.3 V - 5 V
Current	35 mA
Pin Definition	Analog output (Blue wire) Power (Red wire) GND (Black wire)

Size	60 x 20x 6.35 mm
Value Range	0 – 300 (Dry soil) 300 - 700 (Humid soil) 700 - 950 (In water)
Manufacturer	DFRobot
Price	$ 2.47

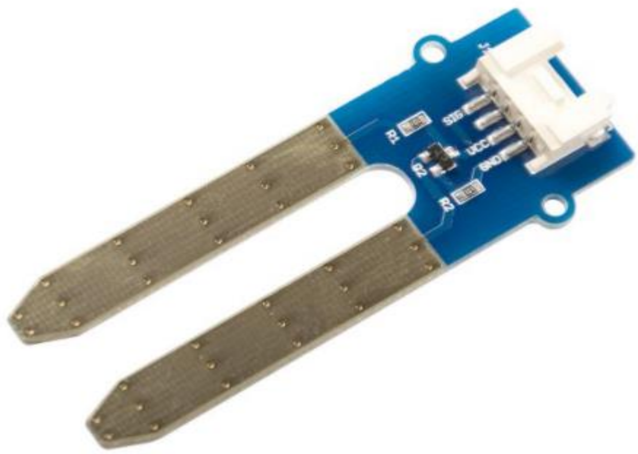

Figure 3.4. Grove – Resistive Soil Moisture Sensor [28]

The main disadvantage of the resistive soil moisture sensors is the corrosion problem of the probes of the sensors. This is not only due to contact of the probes with the soil but also the flowing DC current causes electrolysis of the sensor. This problem can be resolved by using sensor with AC current. And capacitive sensors are capable to do so. Therefore, capacitive soil moisture sensors are preferred over resistive due to their capability to avoid corrosion and provides better readings of the measurement. These are theoretical findings but, in this thesis, we will prove these findings with practical implementation.

3.3 Arduino Uno

Arduino Uno is a microcontroller board based on the ATmega328P-PU. In this thesis, it is used to connect the soil moisture sensors to transmit and receive the data from the sensor. Simplified version of C++ is used to write code and this piece of code run on PC with USB connection between the Arduino board and PC. Figure 3.5 depicts the description of Arduino Uno board.

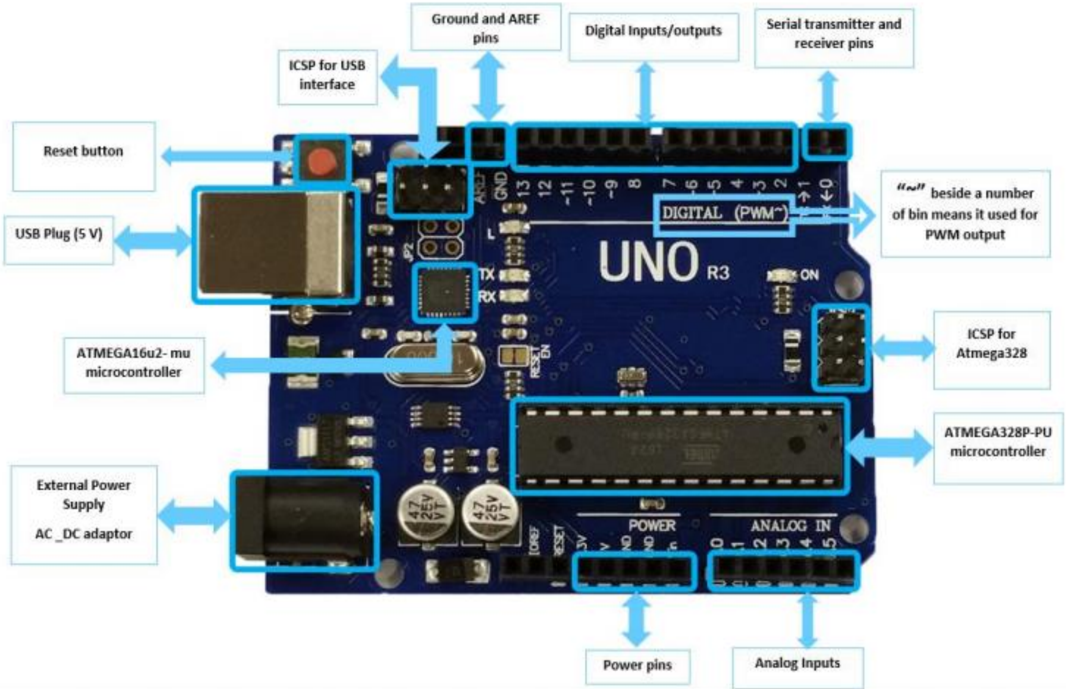

Figure 3.5. Description of Arduino Uno board [29]

The main physical components of Arduino Uno are ATMEGA328P microcontroller which is a 8-bit microcontroller, advanced reduced instruction set computer (RISC) architecture, high endurance non-volatile memory segments, peripheral features and shows higher performance [29].

The technical specifications of the board are available in Table 3.5.

Table 3.5. Technical specifications of Arduino Uno board [30]

Features	**Value**
Microcontroller	ATmega328P-PU
Operating Voltage	5 V
Input Voltage Range	6 – 20 V
Input Voltage Recommendation	7 – 12 V

Digital I/O Pins	14
PWM Digital I/O Pins	6
Analog Input Pins	6
DC Current for 3.3 V Pin	20 mA
DC Current per I/O Pin	50 mA
Flash Memory	32 KB
SRAM	2 KB
EEPROM	1 KB
Clock Speed	16 MHz
LED_BUILTIN	13

3.4 Technical comparison of LoRa and NB-IoT

The IoT devices are perfect due to its highly interoperable, scalable, pervasive and open nature. LPWAN was specifically designed for IoT applications with the purpose of thousands of sensors and applications over a large network. This network protocol is mainly used in smart city applications where there is a need for wide network coverage, but now it has started to be implanted in almost all other social aspects where its properties suit their needs. This Chapter 3 gives an overview of technical comparison of LoRa and NB-IoT technologies to find the feasible technology for the considered use case. Technical comparison of LoRa and NB-IoT is based on physical features, IoT factors such as Quality of Service (QoS), battery life and latency, network coverage and range, deployment model, and cost.

3.4.1 Physical features

LoRa is an open LPWAN system architecture developed and standardized by the LoRa Alliance TM, a non-profit association of more than 500 member companies. On the other hand, NB-IoT operates on licensed spectrum based on Long-Term Evolution (LTE) and it is a Narrow Band IoT technology specified in Release 13 of the 3GPP in June 2016. LoRa is the modulation technique used in the physical layer that enables long-range low-power communications by using Chirp Spread Spectrum (CSS) modulation, which spreads the narrowband signals across a wider channel allowing greater interference resilience and low signal-to-noise ratio levels. CSS was developed in 1940s, was traditionally used in military applications because of its long communication distances and interference robustness. Whereas, NB-IoT uses Orthogonal Frequency Division Multiplexing (OFDM) and Single-Carrier Frequency Division Multiple Access (SC-FDMA) in the downlink and uplink transmission schemes, respectively [31]. Comparison of LoRa and NB-IoT technologies is summarized in Table 3.6.

Table 3.6. Comparison of LoRa and NB-IoT technologies [31]

Specifications	**LoRa**	**NB-IoT**
Modulation	CSS	QPSK
Frequency	Unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia)	Licensed LTE frequency bands
Bandwidth	250 kHz and 125 kHz	200 kHz
Maximum data rate	50 kbps	200 kbps
Maximum messages/day	Unlimited	Unlimited
Maximum payload length	243 bytes	1600 bytes
Interference immunity	Very high	Low

3.4.2 Comparison in terms of IoT factors

These factors should be considered when we choose the suitable technology for an IoT application, including quality of service, latency, battery life, coverage, range, deployment model, and cost.

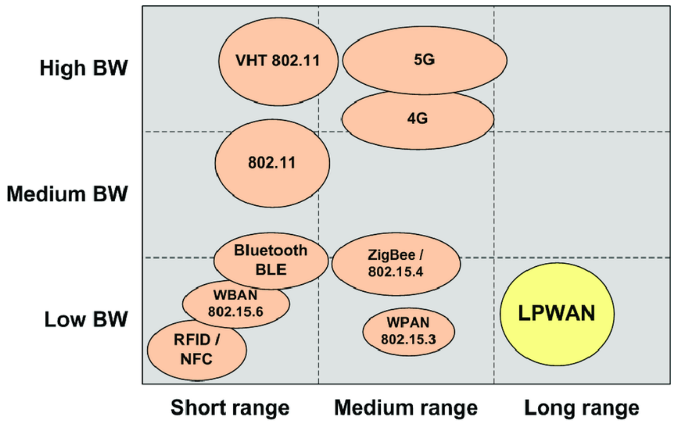

Figure 3.6. Comparison of IoT technologies based on range and bandwidth

Figure 3.6 depicts the comparison of different IoT technologies such as RFID, Bluetooth, Zigbee, Wi-Fi, and LPWAN based on range and bandwidth. LPWAN technologies have long range and low bandwidth.

- **Quality of Service (QoS)**

LoRa based on CSS modulation can handle interference, multipath, and fading but it cannot provide the same QoS as NB-IoT. This is because NB-IoT uses a licensed spectrum and its time slotted synchronous protocol is optimal for QoS. However, this advantage of QoS is at the expense of cost. Licensed band spectrum auctions of the sub-GHz spectrum are typically over 500 million dollars per MHz Because of the trade-off between QoS and high spectrum cost, applications that need QoS prefer the NB-IoT, While the applications that do not need high QoS should choose LoRa [4].

- **Battery life and latency**

In LoRa devices can sleep for as little or as long as the application desires, because it is an asynchronous, Aloha based protocol. On the other hand, because of infrequent but regular synchronization NB-IoT device consumes more battery, and OFDM or FDMA require more peak current for the linear transmitter. These extra energy demands determine that device battery life of NB-IoT is shorter than devices based on LoRa. For applications that require low latency and high data rate, NB-IoT is the better choice [4].

Table 3.7. Comparison based on peak and sleep current, and latency [4]

Technology	Peak current	Sleep current	Latency
LoRa	32 mA	1 µA	Insensitive to latency
NB-IoT	120/130 mA	5 µA	< 10 s

- **Network coverage and range**

The major utilization advantage of LoRa is that a whole city could be covered by one gateway or base station. For example, in Belgium, a country with a total area of approximately 30500 km2, the LoRa network deployment covers the entire country with typically seven base stations. The range of LoRa is < 20 km, for instance, Barcelona city need only three base stations for the whole city. However, the range of NB-IoT is < 10 km and has lowest coverage. It is mainly used with devices which are far from the cellular networks such as indoor places [31]. The deployment of NB- IoT is limited to 4G/LTE base stations. Thus, it is not suitable for rural or suburban regions that do not have 4G coverage. One pivotal benefit of the LoRa ecosystem is its flexibility. LoRa may have a wider network coverage than NB-IoT network. The maximum coupling loss (MCL) is the limit value of the coupling loss at which the service can delivered, and therefore it defines the range of the service [4]. MCL and the range of NB-IoT and LoRa are shown in Table 3.8.

Table 3.8. Comparison based on MCL and range [4]

Technology	Uplink MCL	Downlink MCL	Range
LoRa	165 dB	165 dB	< 15 km
NB-IoT	145 – 169 dB	151 dB	< 35 km

- **Deployment model**

NB-IoT can be deployed by using the concept of reusing and upgrading the existing cellular network but its deployments are only limited to the area supported by cellular network. On the other hand, “the LoRa components and the LoRa ecosystem are mature and production-ready now, although nationwide deployments are still in the rollout phase” [32].

- **Cost**

There is different cost which should be considered namely spectrum cost, network cost, device cost, and deployment cost [4]. Table 3.9 depicts the spectrum cost, network and deployment cost of NB-IoT and LoRa. It can be seen that LoRa is cost effective than NB-IoT.

Table 3.9.Comparison based on cost [4]

Technology	Spectrum cost	Network and Deployment cost
LoRa	Free	$100 - $ 1000/gateway
NB-IoT	>$500 million/MHz	$ 15000/base station

Finally, it can be concluded that LoRa is better choice for smart agriculture due to its device cost, battery life and coverage. So, LoRa is a feasible communication technology for this thesis work.

3.5 LoRa Shield

Author has used Dragino LoRa shield to send data as it allows to reach long range with low data rates. “LoRa shield is a long range transceiver on a Arduino shield form factor and based on Open Source library” [33]. The main advantage of this shied is that it provides ultra-long-range communication with low interference whilst minimum consumption of current.

Figure 3.7. LoRa Shield [33]

Table 3.10. Wireless specification of LoRa Shield [33]

Specifications	**LoRa**
Maximum link budget	168 dB
RF output	+ 20 dBm
Efficiency of PA	+ 14 dBm
Bit rate	300 kbps
Sensitivity	-148 dBm
Modulation technique	FSK, GFSK, MSK, GMSK, LoRaTM, OOK
Dynamic range RSSI	127 dB

In addition, LoRa shield has excellent blocking immunity, built-in bit synchronizer for clock recovery, preamble detection etc. [33]. Overall, this Chapter 3 has covered the all the description of the sensors such as capacitive and resistive soil moisture sensors and LoRa device which has been used for the practical implementation. Experimental set up and results are discussed in the next chapter.

3.6 Types of Soil

For the implementation purpose, author has used three different soils namely clay soil, slit soil, and loam soil. The brief description about these soils is provided in below sections.

- Clay soil

Clay soil consists of fine mineral particles and not organic materials. This soil doesn't have much space between the mineral particles, so it is very sticky. The main benefit of this soil is that it retains moisture because of its density [34].

- Slit soil

Slit soil comprises of medium sized particles which is in between sand and clay soil. This type of soil has limited moisture retention properties and have high fertility rate. This soil is found near the bank of rivers and water bodies [35].

- Loam soil

Loam soil consists of an equal amount of sand and silt and a little amount of clay. It is mainly used in gardening because it is able to retain water easily but also drains quickly. The main properties of loam soil are nutrient-rich, avoid waterlogging, loose, friable etc. Loam soil contains the largest sand proportion, which does not hold moisture and provides air passage and good drainage [36].

4 Experimental Set-Up and Interpretation of Results

In Chapter 4, the experimental set-up and interpretation of results is presented. In the first section, the description of hardware and software is available whereas second section comprised of the practical results such as soil moisture values, temperature values for three different soils.

4.1 Experimental Set-Up

The experimental set-up for this practical work consists both hardware and software. The description of hardware and software is as follows:

- **Hardware Description**
  - Capacitive sensors (V1.0 and V1.2)
  - Resistive sensors (SEN0114 and Grove)
  - Arduino Uno board x 2
  - Laptop/PC x 1
  - Power Bank x 1
  - Dragino LoRa Shield x 2
- **Software Description**
  - Arduino IDE (Integrated Development Environment)
  - The Things Network

Steps involved in the experimental set-up:

1. Preparation of soil and maintenance of the environment.
2. Connection of sensor with Arduino board.
3. Writing of code on Arduino IDE.
4. Connections of Arduino board and Dragino LoRa shield (Gateway and node) and receiving data at the console.

1. Preparation of soil and maintenance of the environment

Soils are prepared by considering the amount of soil and amount of water added to the soil. For instance, if the amount of dry soil (200 g) and 50 ml of water is added to the dry soil, the amount of wet soil becomes 250 g because 1ml is equal to 1g. By using Equation 2.2,

Moisture content (%) = $\frac{250-200}{200} * 100$ = 25%

Similarly, 50% of moisture content is calculated using 200 g of dry soil, and 100 ml of water is added to the dry soil. For 75% of moisture content, 150 ml of water is added to the 200 g of the dry soil. Lastly, 100% of moisture content is achieved by adding 200 ml of water into 200 g of the dry soil.

The maintenance of the environment (temperatures) to perform this experiment. An oven is used to maintain the temperature. For instance, firstly, set the oven at 40^{o}C for five minutes and put soil with 25% moisture content in the oven. Wait for five minutes, then open the lid, place the sensor inside the soil at the recommended depth (datasheet) and close the lid. Data is measured only for one minute to get accurate results at a particular temperature because water starts to evaporate at a higher temperature. The same procedure is repeated for different moisture levels (50%, 75%, and 100%) and temperatures (40^{o}C and 50^{o}C).

The recommended length to insert the probe in the soil is as follows:

- Capacitive soil moisture sensor V1.0 – 3 inches

- Capacitive soil moisture sensor V1.2 – 3 inches
- Resistive soil moisture sensor (SEN0114) – 1.8 inches
- Resistive soil moisture sensor (Grove) – 1.6 inches

2. Connection of sensor with Arduino board

All four sensors have the same pin configuration for the Arduino Uno board. The connections for the pins are described below.

Table 4.1. Pin connections of Arduino Uno board with soil moisture sensors

Arduino Uno Board	Capacitive (V1.0)	Capacitive (V1.2)	Resistive (SEN0114)	Resistive (Grove)
Analog Pin (A_0)	A_0	A_0	A_0	A_0
Ground (GND)	GND	GND	GND	GND
Voltage (3.3 – 5 V)	VCC	VCC	VCC	VCC
Digital (D_0)			D_0	

Table 4.1 shows the pin connections of Arduino Uno board and the four sensors. Three sensors are connected to Arduino Uno board using three pins named as Analog pin (A_0), Ground (GND), Voltage (3.3 – 5 V) whereas SEN01104 resistive soil moisture sensor requires one more pin i.e. Digital (D_0).

For instance, Figure 4.1 depicts the pin connections of resistive soil-moistures sensor with Arduino Uno board where blue wire (A_0 pin) of sensor is connected to corresponding A_0 pin of Arduino Uno board. Similarly, green wire (GND pin) and red wire (3.3 V pin) are connected to corresponding pins of Arduino Uno board.

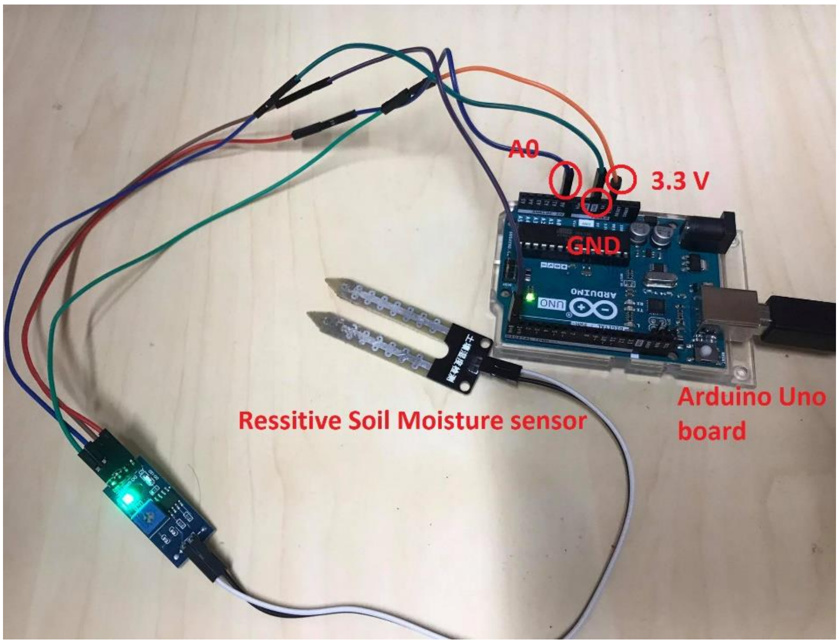

Figure 4.1. Pin connections of resistive soil-moisture sensor with Arduino Uno board

3. Writing of code on Arduino IDE.

Arduino IDE stands for “Integrated Development Environment” which is officially introduced by Arduino.cc. IDE is an open source software which provides a platform for code editing, compiling, and uploading of the code in the Arduino device. IDE environment supports both C and C++ programming languages [37].

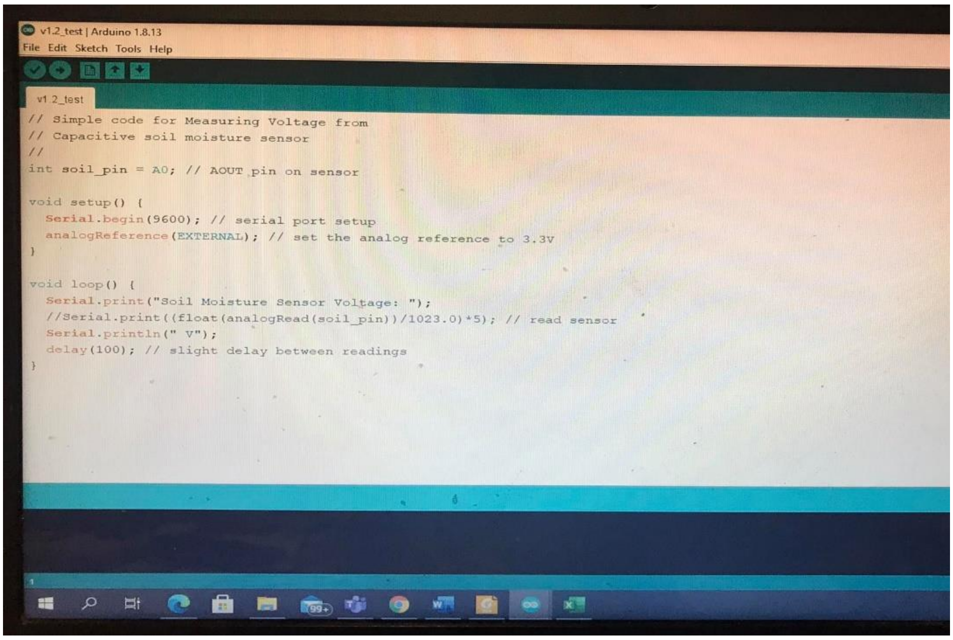

Figure 4.2. Arduino IDE with written code

4. **Connections of Arduino Uno board and Dragino LoRa shield (Gateway and node).**

The steps involve in connecting Arduino Uno board with Dragino LoRa shield are as follows:

- Attach the LoRa shields to Arduino board in which one acts as client and another one is server.
- Before starting the program, set the frequency according to LoRa i.e. 868 MHz as per EU regulations.
- Open Arduino IDE and run the program. Eventually, gateway and node will be created, and it will start receiving the data at console.

Figure 4.3. Attached pair of LoRa and Arduino board which acts as a server and client [38]

Figure 4.3 depicts the attached pair of LoRa and Arduino board where one pair act as server and another as client. Moreover, the source code of gateway and node are available in Appendix 1.

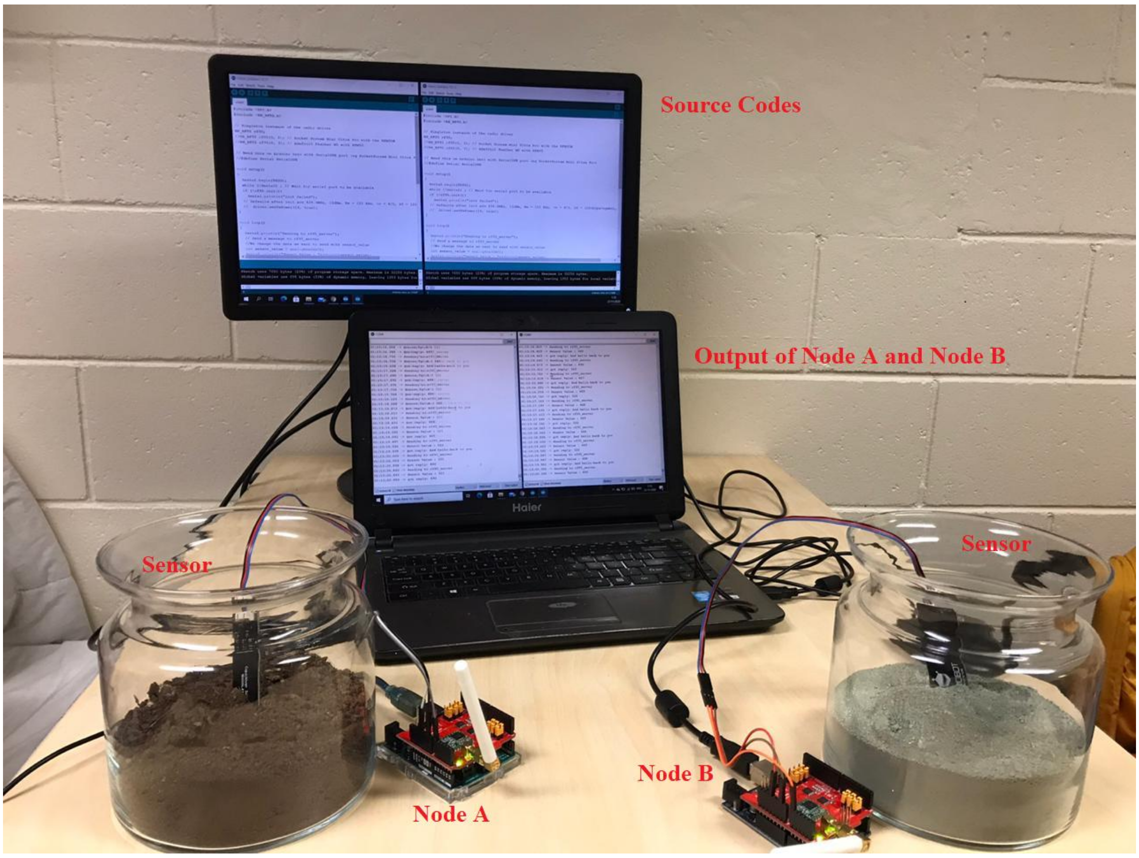

Figure 4.4. Experimental set-up

4.2 The Things Network (TTN)

It is an open platform, to build your next IoT application at low cost, featuring maximum security and ready to scale. In order to get data on TTN we have to do some changes on code. Like changing Network session key, app session key and device address. This key will be given by TTN while registering our node [39].

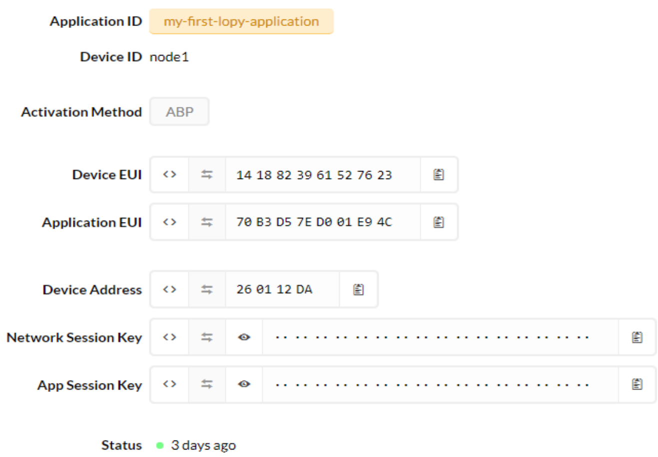

Figure 4.5. Registration of node on TTN

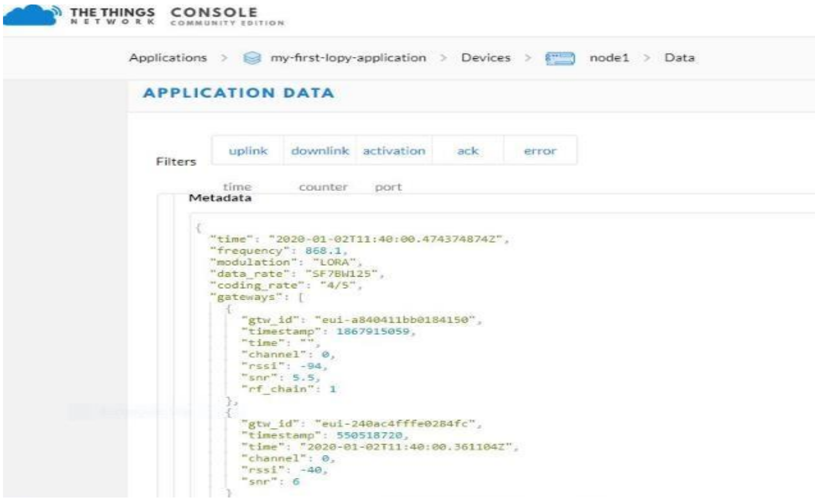

Figure 4.6. Receiving data on console

Received Signal Strength Indicator (RSSI) is an indication of the power level being received by the receiving radio after the antenna and possible cable loss. The higher the RSSI number, the stronger the signal. Thus, when an RSSI value is represented in a negative form (e.g. −100), the closer the value is to 0, the stronger the received signal.

4.3 Experimental Results

Experimental results are discussed in this section and these are categorized in four parts according to four soil moisture sensors. The experiment is performed to get the readings of sensor using three soils namely clay, loam and silt for three temperatures such as room temperature, 40^{o}C and 50^{o}C. Finally, the measured readings of sensor are compared with values of data sheet to check the accuracy of the sensor i.e. how measured and actual values closely related. The measured values of the sensor reflect the state of the soil, is it dry, wet or watery. The actual values for these states vary from sensor to sensor because these values are defined by manufacturer.

4.3.1 Capacitive soil moisture sensor V1.0

- At room temperature

The experiment is performed at room temperature for four values of water content i.e. 25%, 50%, 75% and 100%. Table 4.2 shows the sensor reading for clay, loam and silt soils with different moisture content at room temperature. According to data sheet [25], Dry state: [520 , 430]; Wet state: [430 , 350]; Watery state: [350 , 260].

For clay soil, with 25% of moisture content the sensor reading shows that soil is in dry state because the value lies between 430 to 520 which is defined for dry state. In addition, the sensor readings for other moisture contents lies between the watery state conditions. This is because of the water retention property of clay soil where this soil absorbs water and become thick.

Table 4.2. Sensor (Capacitive soil moisture sensor V1.0) readings for clay, loam and silt soils with different moisture content at room temperature

Moisture content (%)	Clay soil	Loam soil	Silt soil
25	436	460	434
50	334	444	340
75	332	330	308
100	288	306	262

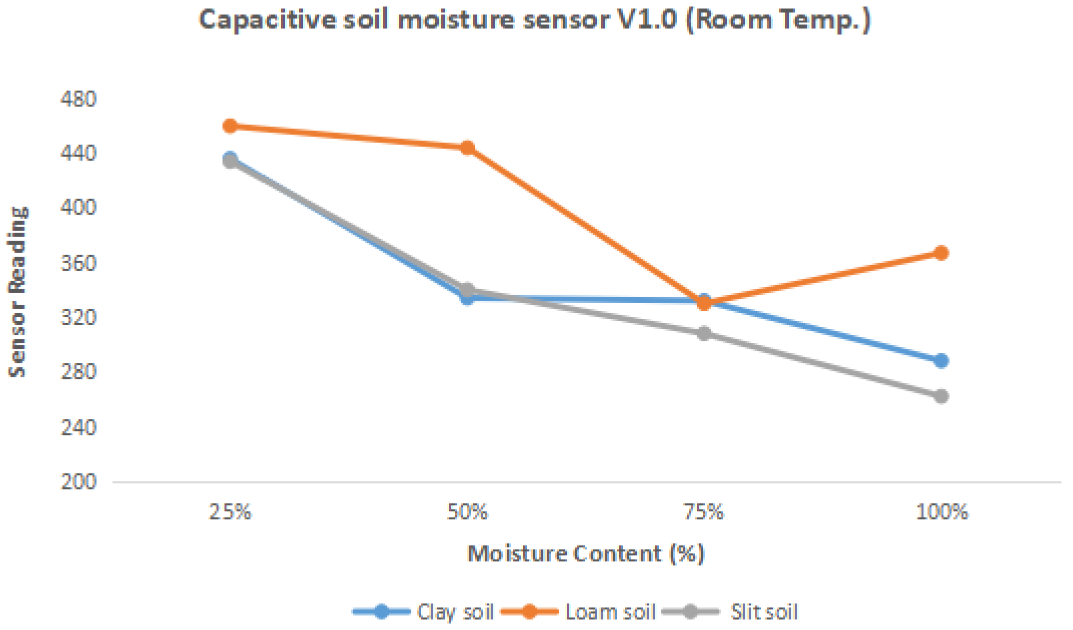

Figure 4.7. Moisture content vs sensor readings at room temperature, Capacitive soil moisture sensor V1.0

For loam soil, as the Figure 4.7 indicates the sensor reading is 460 and 444 for 25% and 50% of water content which lies in the range of dry state because the water distribution is uniform in the soil. Moreover, for 75% and 100% of water content, the sensor reading shows watery state of soil.

As explained in the section 3.6, silt soil is combination of clay and loam soil. The sensor readings show 434 (dry state, 25% of water content) then for 50%, it shows close to wet state. Lastly, the soil state is watery for 75% and 100% of water content.

- At 40^{o}C

Table 4.3 shows the Sensor (Capacitive soil moisture sensor V1.0) readings for clay, loam and silt soils with different moisture content at 40^{o}C. During experiment, it was noticed that the evaporation was happening due to high temperature. The sensor readings were rapidly changing due to this evaporation. However, clay soil was able to absorb the water so it shows wet and watery conditions but the loam soil and silt were not able to hold water at this temperature, so the sensor reading shows almost dry state i.e. has little moisture for 25% and 50% of water content.

Table 4.3. Sensor (Capacitive soil moisture sensor V1.0) readings for clay, loam and silt soils with different moisture content at 40^{o}C

Moisture content (%)	**Clay soil**	**Loam soil**	**Silt soil**
25	462	444	433
50	351	421	404
75	281	330	330
100	278	297	291

Figure 4.8 depicts the moisture content vs sensor reading at 40^{o}C. At this temperature, the loam soil and silt soil almost show same behaviour of soil states whereas at room temperature, the clay soil and silt soil show same behaviour as shown in Figure 4.7.

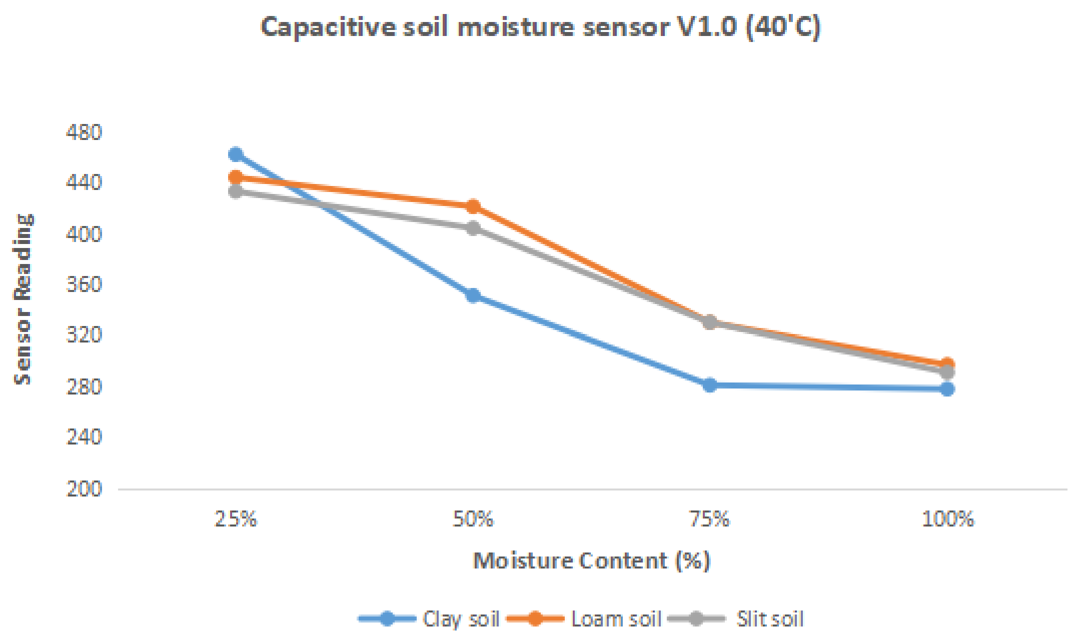

Figure 4.8. Moisture content vs sensor readings at 40ºC, Capacitive soil moisture sensor V1.0

- At 50ºC

Table 4.4 shows the Sensor (Capacitive soil moisture sensor V1.0) readings for clay, loam and silt soils with different moisture content at 50ºC. It was noticed that the evaporation was more at this temperature. Eventually, there was drastic change in the sensor readings i.e. wet state was changing to dry state instantly. At 50ºC, the sensor shows highest value of dry state i.e. 491. It can be analyzed form the Table 4.4 that only clay soil was able to absorb water and shows watery state but other two soils did not show watery state because, they lose the moisture because of high. temperature

Table 4.4. Sensor (Capacitive soil moisture sensor V1.0) readings for clay, loam and silt soils with different moisture content at 50ºC

Moisture content (%)	Clay soil	Loam soil	Silt soil
25	491	464	440
50	404	410	400
75	309	363	350
100	283	344	310

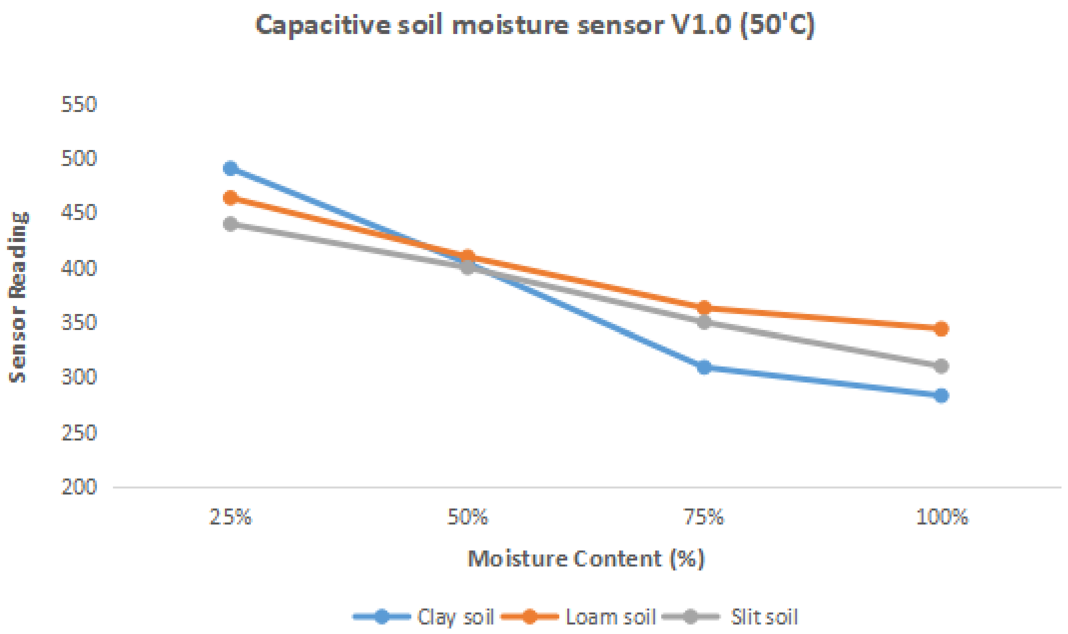

Figure 4.9. Moisture content vs sensor readings at 50ºC, Capacitive soil moisture sensor V1.0

4.3.2 Capacitive soil moisture sensor V1.2

The experiment is performed at room temperature for four water content values, i.e., 25%, 50%, 75% and 100%. Table 4.3 shows the sensor reading for clay, loam and silt soils with different moisture content at room temperature. According to data sheet [25], Dry state: [520 , 430]; Wet state: [430 , 350]; Watery state: [350 , 260].

Table 4.5. Sensor (Capacitive soil moisture sensor V1.2) readings for clay, loam and silt soils with different moisture content at room temperature

Moisture content (%)	**Clay soil**	**Loam soil**	**Silt soil**
25	459	407	405
50	435	443	424
75	324	336	316
100	303	305	337

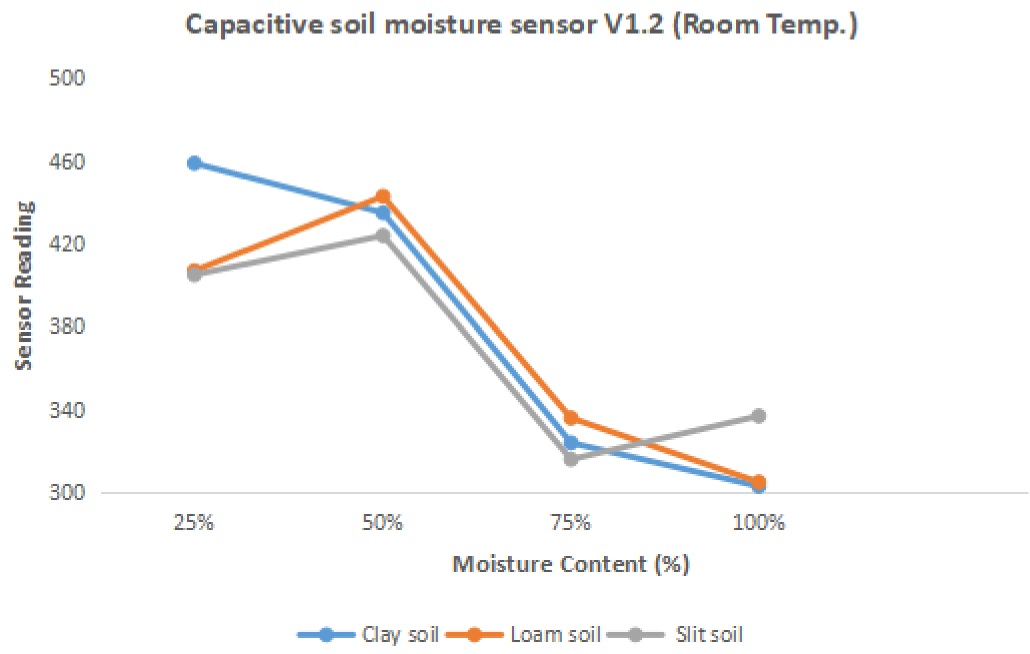

Figure 4.10. Moisture content vs sensor readings at room temperature, Capacitive soil moisture sensor V1.2

Figure 4.10. depicts the moisture content vs sensor reading at room temperature. It can be noticed from the Figure 4.10 that the sensor behaves accurately with the clay soil as firstly it showed dry state followed by wet and watery whereas sensor behaves differently with loam and silt by showing web state first instead of dry state. So, it can be concluded that the sensor is not able to work correctly for loam and silt soil.

- At 40^{o}C

Table 4.6 shows the Sensor (Capacitive soil moisture sensor V1.2) readings for clay, loam and silt soils with different moisture content at 40^{o}C. The sensor behaves accurately for clay soil at this temperature and shows all the three soil states i.e. dry, wet and watery. But the sensor readings show only dry and wet state for the loam and silt soil.

Table 4.6. Sensor (Capacitive soil moisture sensor V1.2) readings for clay, loam and silt soils with different moisture content at 40^{o}C

Moisture content (%)	**Clay soil**	**Loam soil**	**Silt soil**
25	425	464	421
50	346	415	388

75	285	352	350
100	260	318	322

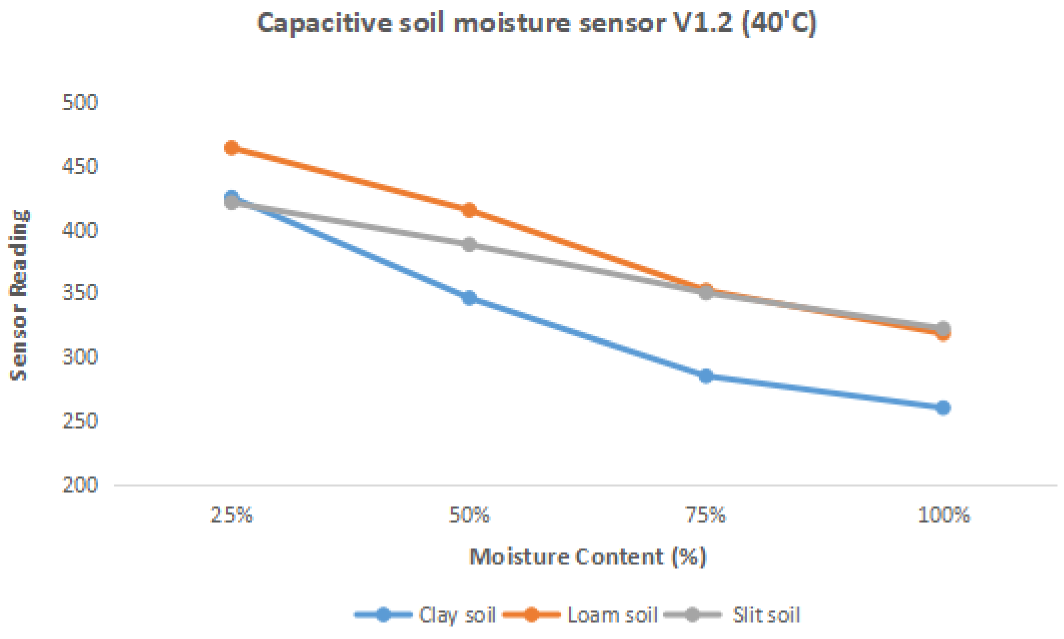

Figure 4.11. Moisture content vs sensor readings at 40°C, Capacitive soil moisture sensor V1.2

It can be concluded from the Figure 4.11 that loam soil do not have water absorption property as the maximum proportion of this soil consists of large sand particles which is responsible for water drainage. Due to this, the sensor readings show dry and wet states but not watery state. In addition, silt soil has medium sized particles, so it shows small values of dry states as compare to loam soil. Furthermore, the sensor readings are same for loam and silt soil for 75% and 100% water content, but these readings should be different because the properties are soil are different.

- At 50°C

Table 4.7 shows the Sensor (Capacitive soil moisture sensor V1.2) readings for clay, loam and silt soils with different moisture content at 50°C. The sensor behaves accurately for clay soil at this temperature and shows all the three soil states i.e. dry, wet and watery. However, sensor readings show dry and wet states for both loam and silt soil with25%, 50% and 75% of water content.

Table 4.7. Sensor (Capacitive soil moisture sensor V1.2) readings for clay, loam and silt soils with different moisture content at 50°C

Moisture content (%)	Clay soil	Loam soil	Silt soil
25	451	461	450
50	360	424	411
75	316	380	350
100	220	346	260

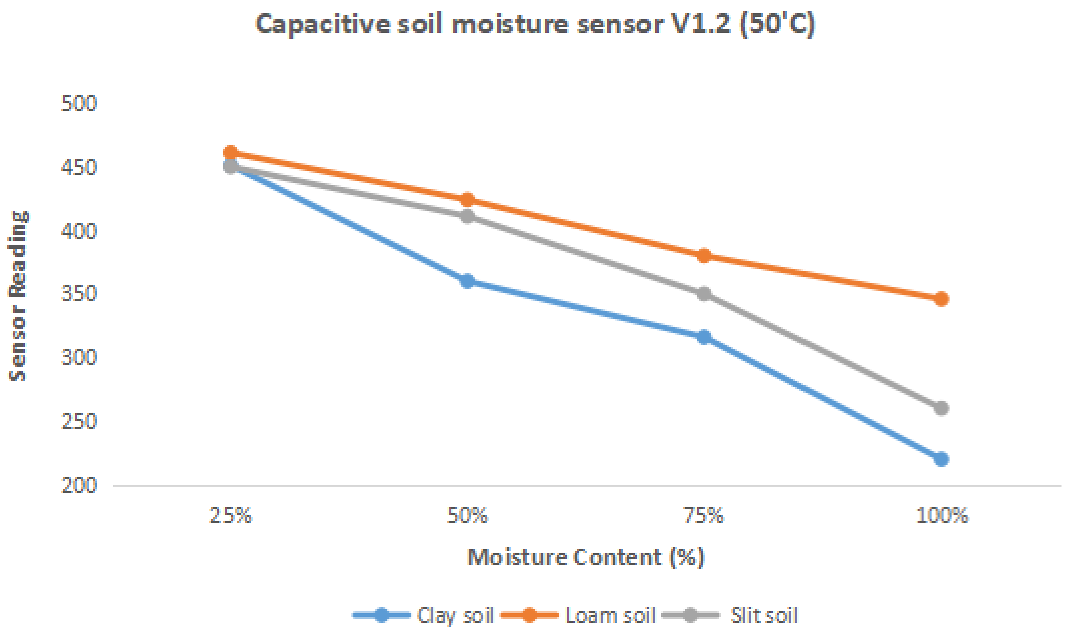

Figure 4.12. Moisture content vs sensor readings at 50°C, Capacitive soil moisture sensor V1.2

This sensor is not reliable because it shows 322 for 100% water content at 40°C but it shows 260 for same water content at 50°C which is inaccurate because the value should be higher as increase in the temperature. It is well known that dryness increases with increase in temperature.

4.3.3 Resistive soil moisture sensor (SEN0114)

The experiment is performed at room temperature for four values of water content i.e. 25%, 50%, 75% and 100%. Table 4.2 shows the sensor reading for clay, loam and silt soils with different moisture content at room temperature. According to data sheet, Dry state: [Above 750]; Wet state: [750 , 500]; Watery state: [500 , 0].

Table 4.8. Sensor (Resistive soil moisture sensor, SEN0114) readings for clay, loam and silt soils with different moisture content at room temperature

Moisture content (%)	Clay soil	Loam soil	Silt soil
25	363	624	662
50	368	659	722
75	243	462	539
100	198	154	223

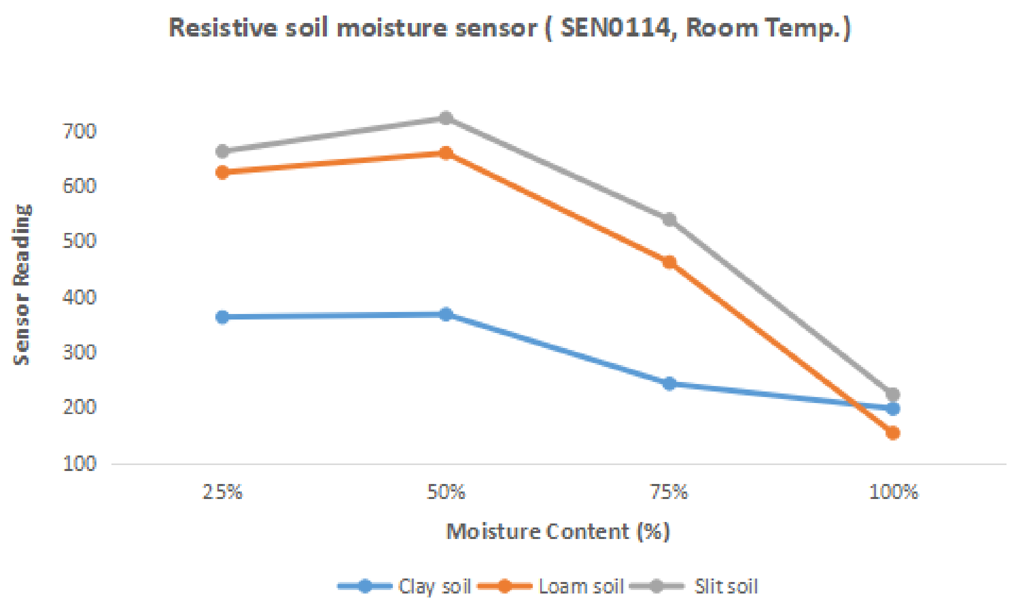

Figure 4.13. Moisture content vs sensor readings at room temperature, Resistive soil moisture sensor (SEN0114)

Figure 4.13 depicts the moisture content vs sensor readings at room temperature. It can be analyzed that sensor readings are less than 500 i.e. in water state with clay soil for all the values of water content. Both loam and silt soils do not have dry state but shows wet state within the range of 500-750 for 25% and 50% water content and also shows watery state with values < 500 for 75% and 100% water content.

- At 40°C

Table 4.9 shows the Sensor (Resistive soil moisture sensor, SEN0114) readings for clay, loam and silt soils with different moisture content at 40°C. For clay soil, sensor shows wet state (536) with 25% of water content at 40°C whereas it showed watery state for same water content at room temperature, it means sensor behavior is accurate for clay soil.

Table 4.9. Sensor (Resistive soil moisture sensor, SEN0114) readings for clay, loam and silt soils with different moisture content at 40°C

Moisture content (%)	Clay soil	Loam soil	Silt soil
25	536	744	767
50	432	684	590
75	208	436	396
100	198	281	238

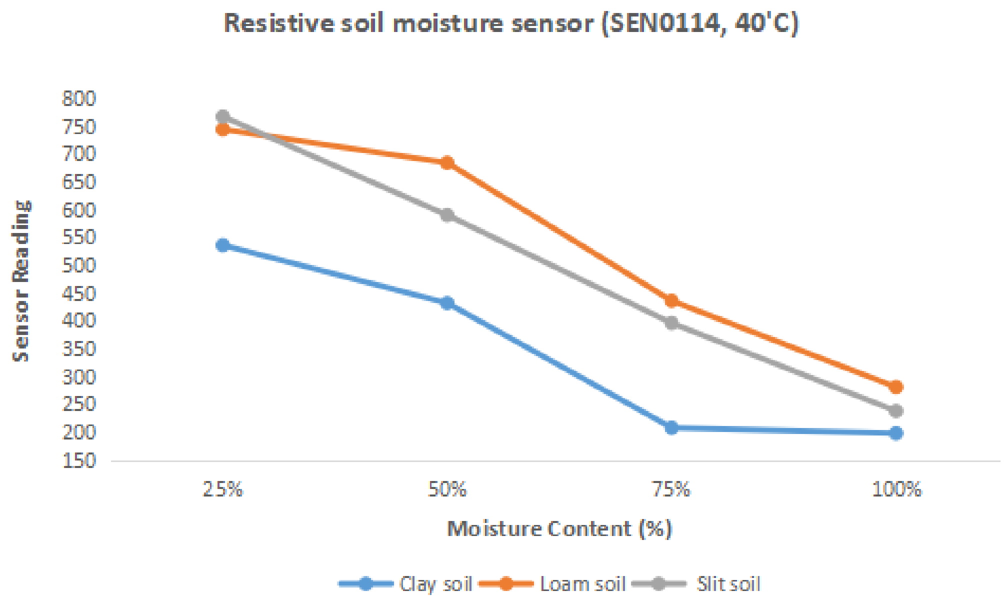

Figure 4.14. Moisture content vs sensor readings at 40°C, Resistive soil moisture sensor (SEN0114)

Loam and silt soil have almost dry and dry state respectively with increase in temperature. Also, both soils have wet and watery states. So, it can be concluded that the sensor behaves accurately at 40°C.

- At 50°C

Table 4.10 shows the Sensor (Resistive soil moisture sensor, SEN0114) readings for clay, loam and silt soils with different moisture content at 50°C. The behavior of sensor is approximately same at temperatures 40°C and 50°C.

Table 4.10. Sensor (Resistive soil moisture sensor, SEN0114) readings for clay, loam and silt soils with different moisture content at 50ºC

Moisture content (%)	Clay soil	Loam soil	Silt soil
25	492	612	703
50	380	553	620
75	257	408	410
100	193	260	298

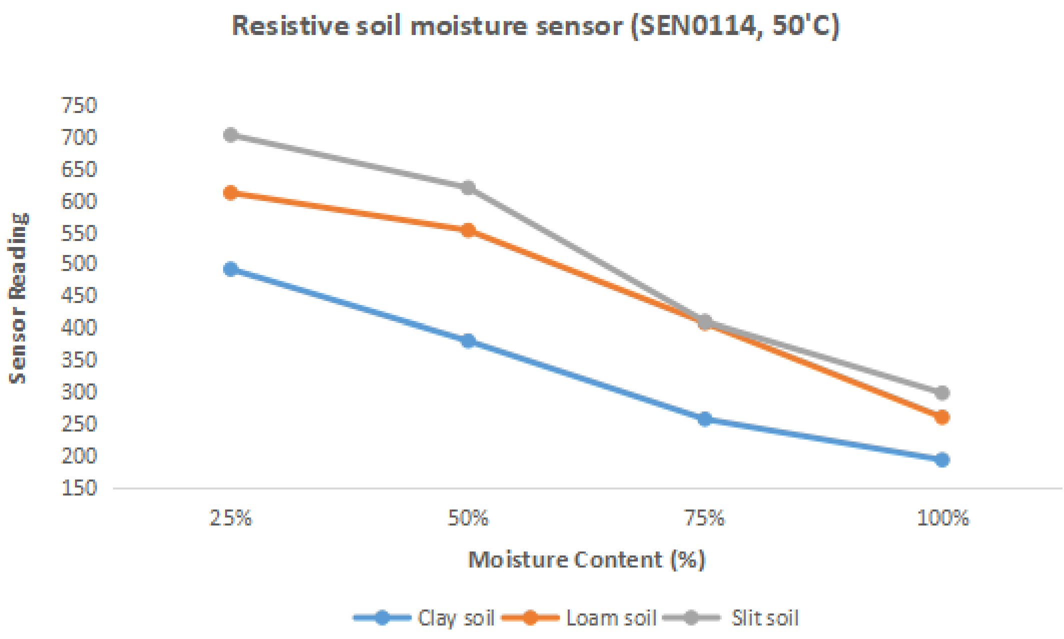

Figure 4.15. Moisture content vs sensor readings at 50ºC, Resistive soil moisture sensor (SEN0114)

The main drawback of this sensor is that it gets corroded during the experimental phase. So, this sensor is not reliable for agricultural applications because durability and corrosion resistive are the main requirements for these applications.

4.3.4 Resistive soil moisture sensor (Grove)

The experiment is performed at room temperature for four values of water content i.e. 25%, 50%, 75% and 100%. Table 4.2 shows the sensor reading for clay, loam and silt soils with different moisture content at room temperature. According to data sheet, Dry state: [0, 300]; Wet state: [300 , 700]; Watery state: [700 , 950].

Table 4.11 shows the Sensor (Resistive soil moisture sensor, Grove) readings for clay, loam and silt soils with different moisture content at room temperature. The sensor reading shows watery state for 25%, 75% and 100% water content but wet state (579) for 50% water content in clay soil. Loam soil has watery state for all values of water content at room temperature whereas silt soil has wet state for 25% and 50% water content and watery state for 75% and 100%.

Table 4.11. Sensor (Resistive soil moisture sensor, Grove) readings for clay, loam and silt soils with different moisture content at room temperature

Moisture content (%)	Clay soil	Loam soil	Silt soil
25	785	712	619
50	579	743	664
75	818	772	794
100	826	793	820

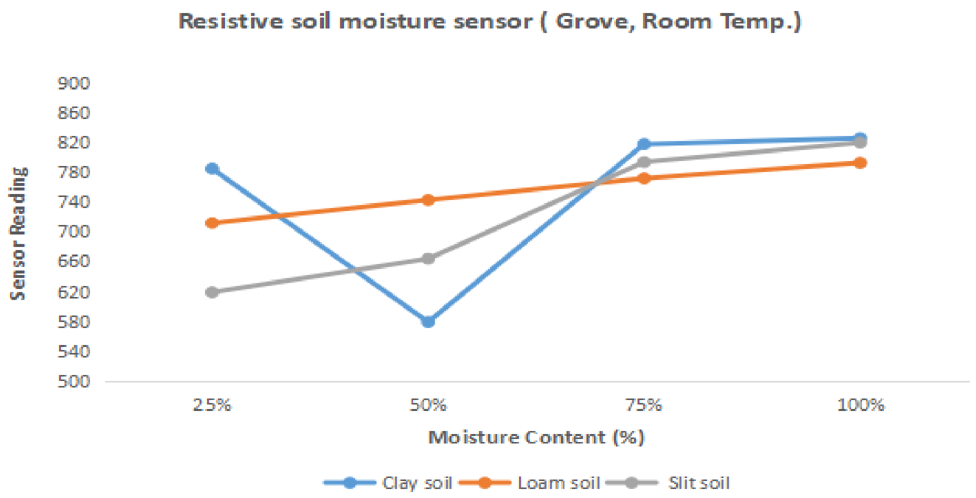

Figure 4.16. Moisture content vs sensor readings at room temperature, Resistive soil moisture sensor (Grove)

It can be observed from the Figure 4.16 that the behavior of sensor is not accurate as it is showing watery state with little water content. It means the sensor is not reliable and can't be used for agriculture applications.

- At 40°C

Table 4.12 shows the Sensor (Resistive soil moisture sensor, Grove) readings for clay, loam and silt soils with different moisture content at 40°C. It can be observed from the below table that clay soil has watery state for all the values of water content even at 40°C. As the state of the soil should be changes with increase in temperature.

Table 4.12. Sensor (Resistive soil moisture sensor, Grove) readings for clay, loam and silt soils with different moisture content at 40°C

Moisture content (%)	Clay soil	Loam soil	Silt soil
25	751	480	591
50	797	687	700
75	821	807	743
100	855	818	813

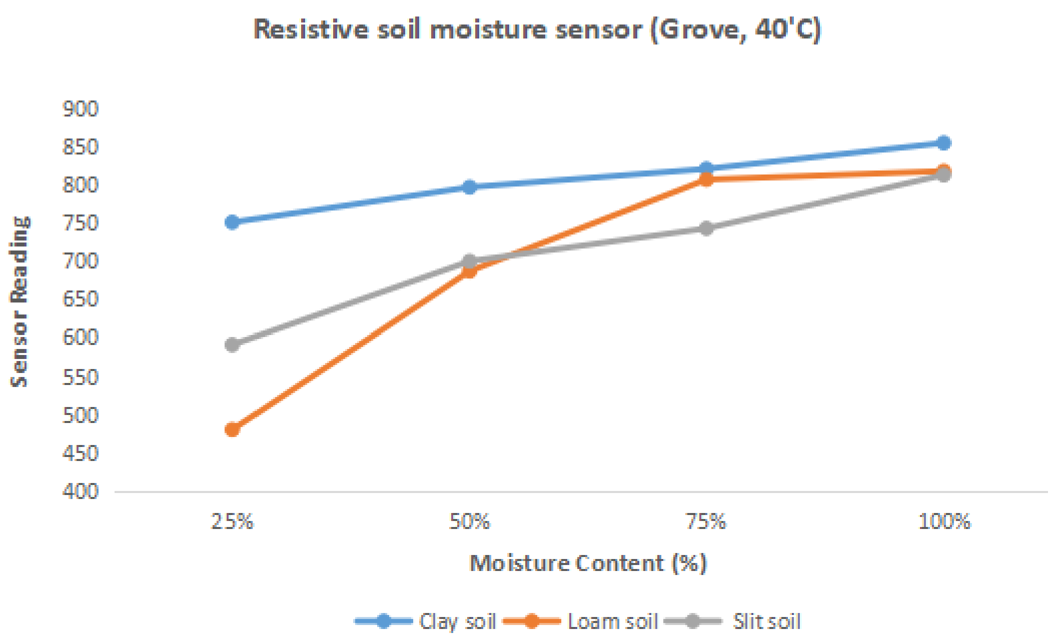

Figure 4.17. Moisture content vs sensor readings at 40°C, Resistive soil moisture sensor (Grove)

Moreover, the results of the sensor with loam and silt soil are also unacceptable because the difference of measured data and actual data is more. It means the sensor is not working accurately at 40°C. This sensor is not suitable for agricultural applications due to inaccurate measurements.

- At 50°C

Table 4.13 shows the Sensor (Resistive soil moisture sensor, Grove) readings for clay, loam and silt soils with different moisture content at 50°C. It can be observed from the below table that clay soil has watery state for the values of water content (50%, 75% and 100%) even at 50ºC.

Table 4.13. Sensor (Resistive soil moisture sensor, Grove) readings for clay, loam and silt soils with different moisture content at 50ºC

Moisture content (%)	Clay soil	Loam soil	Silt soil
25	652	398	540
50	716	601	710
75	823	842	800
100	854	832	843

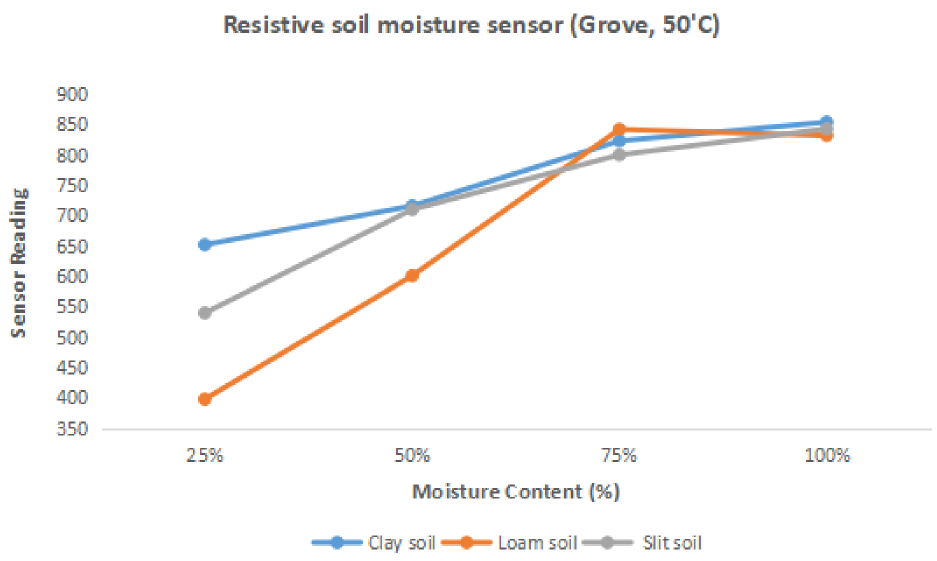

Figure 4.18. Moisture content vs sensor readings at 50ºC, Resistive soil moisture sensor (Grove)

It can be concluded from the Figure 4.17 that the sensor is behaving accurately as it is showing almost dry state with less water content and watery state with more water content. But the sensor is inaccurate as it the deviation of the measure values for every state is more from the actual values i.e. given by manufacturer.

4.4 Result Discussions

This section discusses the results according to the perspective of soils such as clay, loam, and silt soil. The accuracy of the sensors is analyzed by noticing their behavior in different soils at different temperatures. The sensor's respective manufacturer defines the values for dry, wet, and in water states. All the sensors have the same trend of values, such as the minimum for in-water and maximum for dry state except the resistive grove sensor. However, it can be concluded by analyzing the results of section 4.3.4 that the grove sensor is the most inaccurate because it shows maximum deviation from the soil state's actual values, which are defined by the manufacturer. So, only three sensors, namely Capacitive V1.0, Capacitive V1.2, and Resistive (SEN0114) soil moisture sensors, are used for the comparison.

- Clay soil

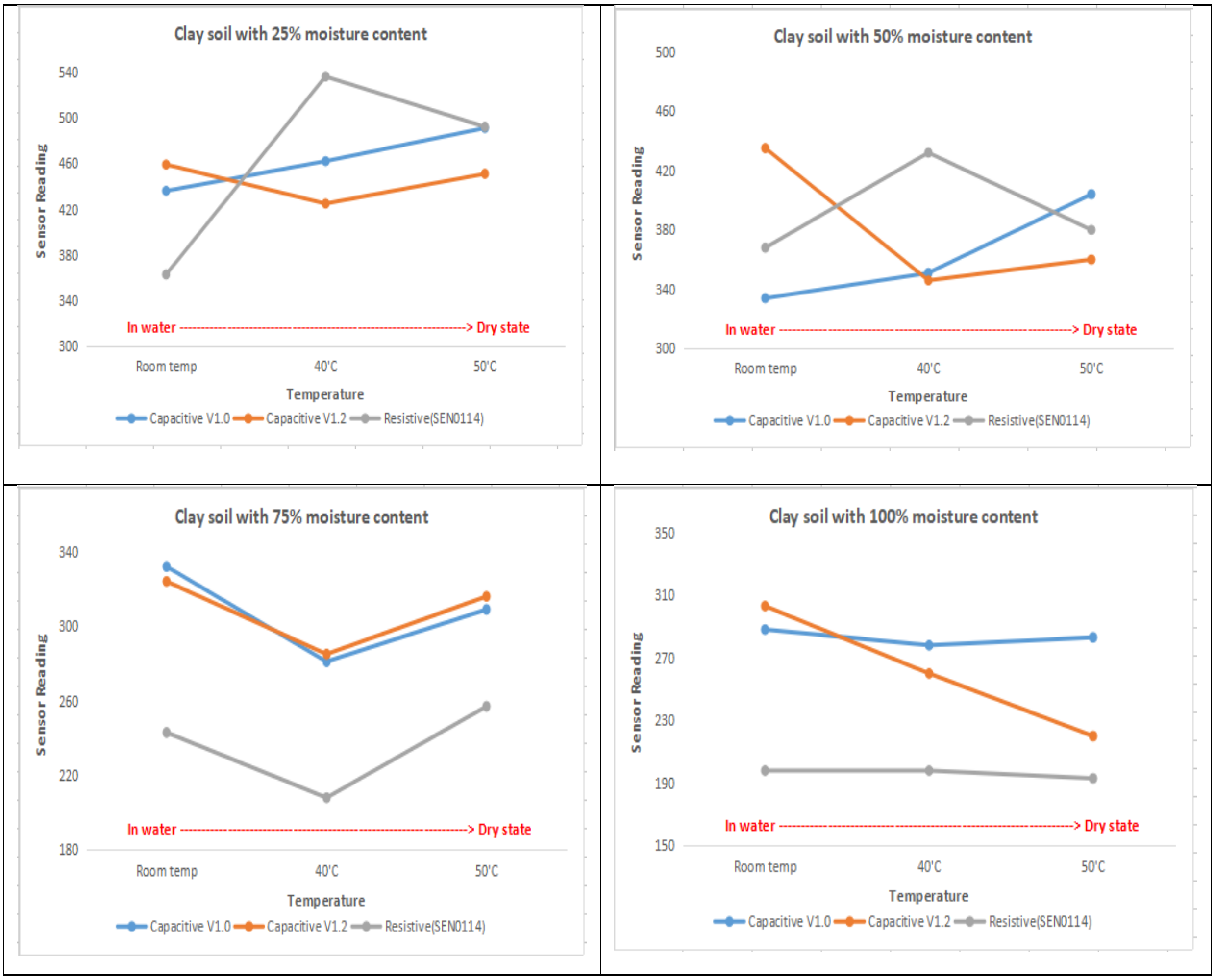

Figure 4.19. The behavior of sensors in clay soil

Figure 4.19 depicts the behavior of sensors in clay soil at different moisture levels and temperature. Clay soil consists of small particles and has water retention properties. Capacitive V1.0 sensor shows the dry states for less water content (25% and 50%) because the soil dries with an increase in temperature. As the water content increases (75% and 100%), it only shows wet and watery because clay soil absorbs the water and becomes sticky. Capacitive V1.2 sensor shows more deviation from the actual values (Dry state: [520 , 430]; Wet state: [430 , 350]; Watery state: [350 , 260]) as compare to Capacitive V1.0. Moreover, the actual values for soil states of resistive (SEN0114) sensor are dry state: [Above 750]; Wet state: [750 , 500]; Watery state: [500 , 0]. This sensor is the least accurate compared to the capacitive sensors because it behaves correctly for higher water content, but with lower water content, it shows inaccurate behavior. For instance, with 25% and 50% water content, the sensor reading should increase towards the dry state, but it started decreasing for 50^{o}C temperature. Overall, Capacitive V1.0 behaves correctly according to the clay soil properties.

- Loam soil

Figure 4.20 depicts the behavior of sensors in loam soil at different moisture levels and temperature. Loam soil contains the largest proportion of sand, which does not hold moisture or drains quickly. It can be seen from the below figure that capacitive sensors show approximately the same behavior by reading revolves around the wet state at room temperature, 40^{o}C, and 50^{o}C, i.e., loam soil absorbs water quickly and drains easily. So, the capacitive sensor readings are almost similar except for the 75% water content. Resistive (SEN0114) soil moisture sensor reads nearly dry states for 25% water content, but it behaves unexpectedly for 50% water content as it reads wet state for higher temperature. Overall, it is tough to understand the behavior of the resistive sensor with loam soil.

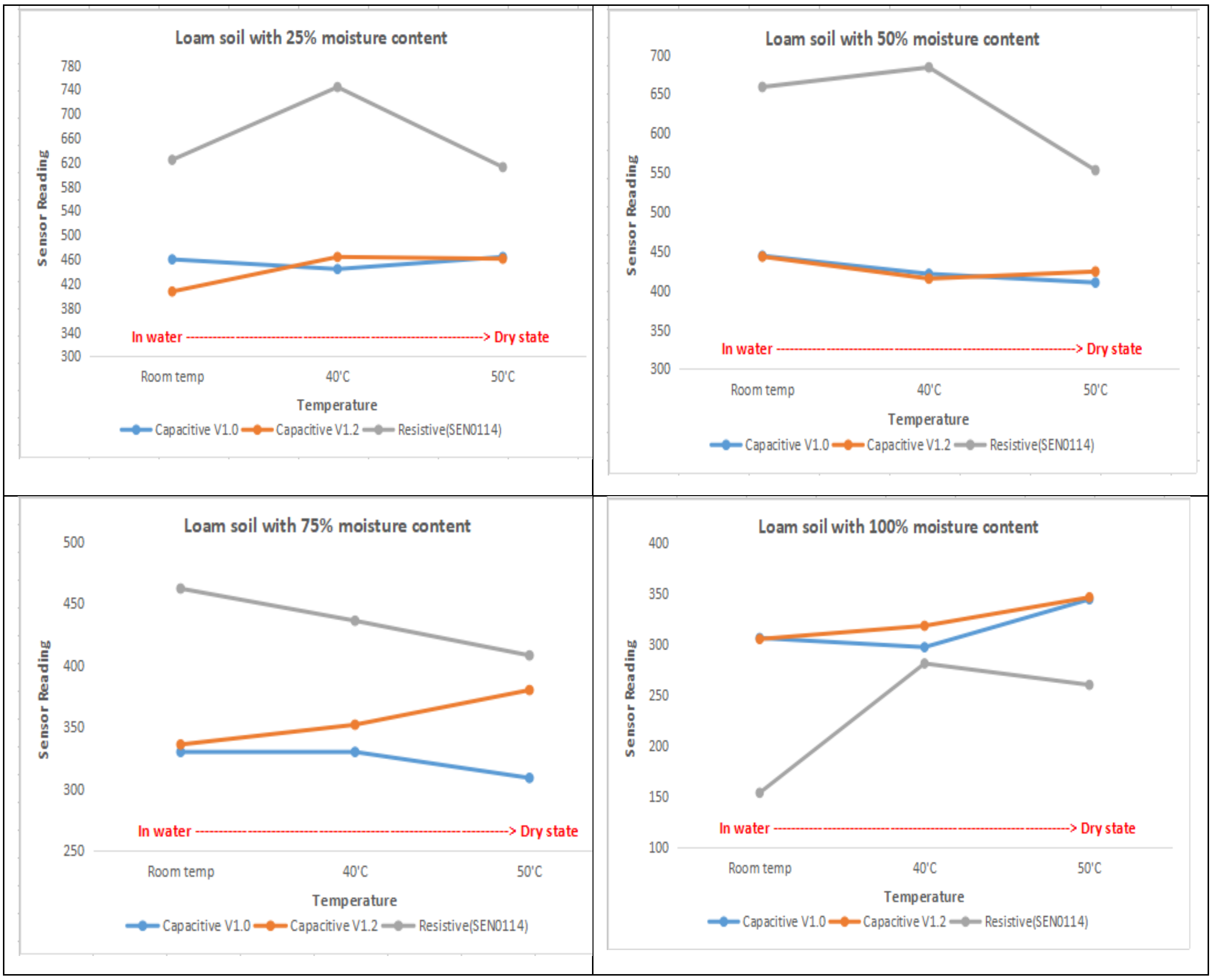

Figure 4.20. The behavior of sensors in loam soil

- Silt soil

Figure 4.21 depicts the behavior of sensors in silt soil at different moisture levels and temperature. Silt soil consists of medium size particles and has some proportion of clay soil. So, its water retention capability lies between loam and clay soil. Both the capacitive sensors read the wet states for all the moisture content with little variation because silt soil has medium water retention property, and the sensor reading lies in the range of the wet state. But the curve is different for 100% water content. Even though both the sensors' reading lies in the wet state range, the trend is different, i.e., Capacitive V1.0 shows an upward trend, whereas Capacitive V1.2 shows a downward trend. Overall, it can be concluded that the Capacitive V1.0 sensor is more accurate because it maintains the same behavior for all the water content levels as compare to Capacitive V1.2. The resistive sensor has shown different behavior for all the moisture content levels, which makes it inaccurate because it is hard to understand how it behaves in silt soil.

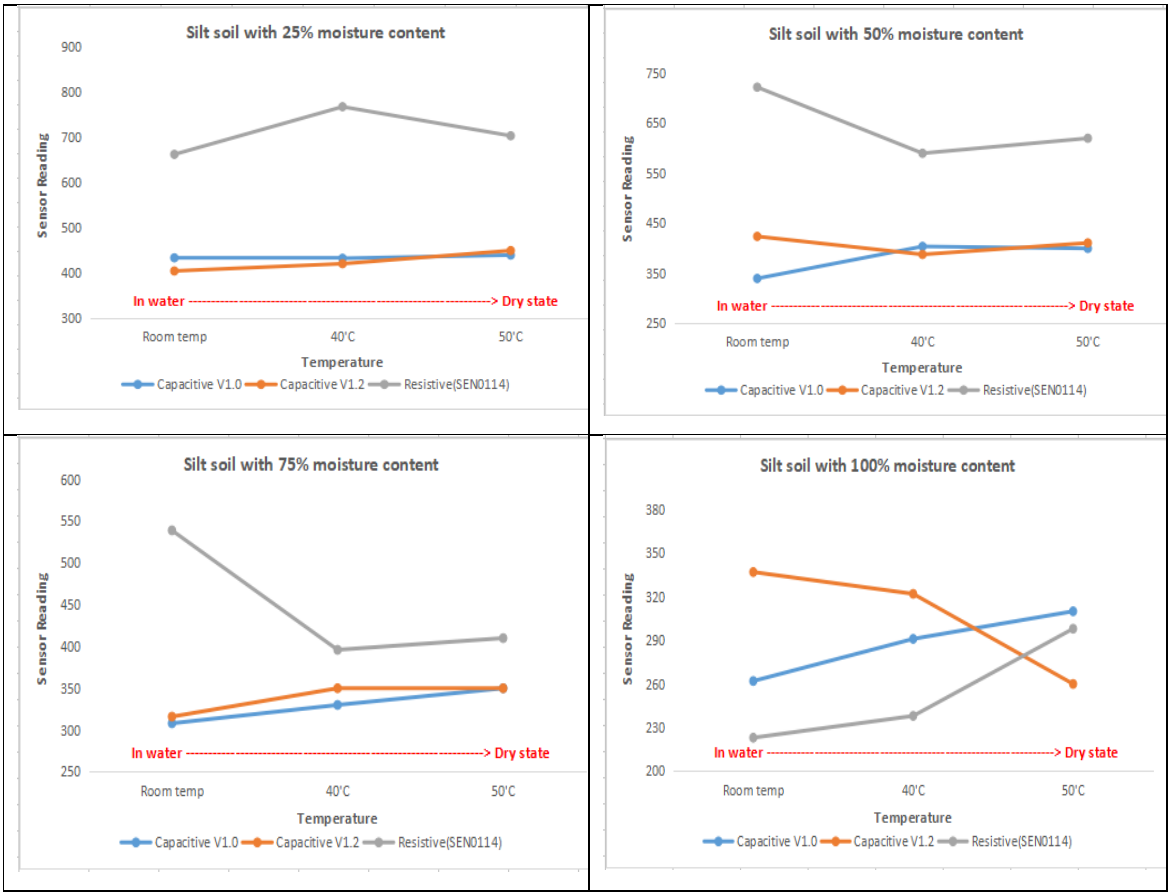

Figure 4.21. The behavior of sensors with silt soil

Based on the above results, it can be concluded that capacitive soil moisture sensors are more accurate and reliable than resistive soil moisture sensors because these provide better measurement readings and avoid corrosion. The corrosion in resistive soil moisture sensors is not only because of the contact of probes with soil but also due to electrolysis of the sensors. The corrosion problem makes these sensors less durable. Table 4.14 depicts the comparison of these four sensors based on cost, manufacturer, accuracy, corrosion resistance, and durability.

Table 4.14. Comparison of four different soil moisture sensors

Characteristics	Capacitive V1.0	Capacitive V1.2	Resistive SEN0114	Resistive Grove
Cost	$ 1.50	$ 0.72	$ 1.59	$ 2.47
Manufacturer	DFRobot	Paialu	AZDelivery	DFRobot
Accuracy	Most accurate	Less than V1.0	Less than V1.0 and V1.2	Least accurate
Corrosion Resistance	Yes	Yes	No	No
Durability	Most durable	Most durable	Not durable	Less durable

Based on the comparison given in Table 4.14, Capacitive V1.0 sensor is most accurate, corrosion resistant and most durable among all the sensors whereas capacitive V1.2 is less accurate than V1.0 but it is also corrosion resistant , most durable and cheaper. There is trade-off between accuracy and cost. Capacitive V1.0 is costly than V1.2 but have more accuracy while V1.2 is cheaper than V1.0 but have less accuracy. So, both can be used for agricultural applications based on the requirements such as accuracy or cost. On the other hand, as mentioned above resistive sensors are less accurate, corrode easily, costly, and less durable.

4.5 LoRa Results

After creating gateway and nodes, data is received on console. Range is tested inside building. And the measured range for the experiment is 50 m. It is less because of indoor location as device get more interference due to blocks as well as absence of proper gateway. For this experiment, author has created a dummy gateway which is only able to work for smaller range. But LoRa is able to work up to 15 km [4]. So, farmers can deploy the device in the field and monitor data within the range of 15 km. Figure 4.17 shows an example of data monitoring in the control room or own device.

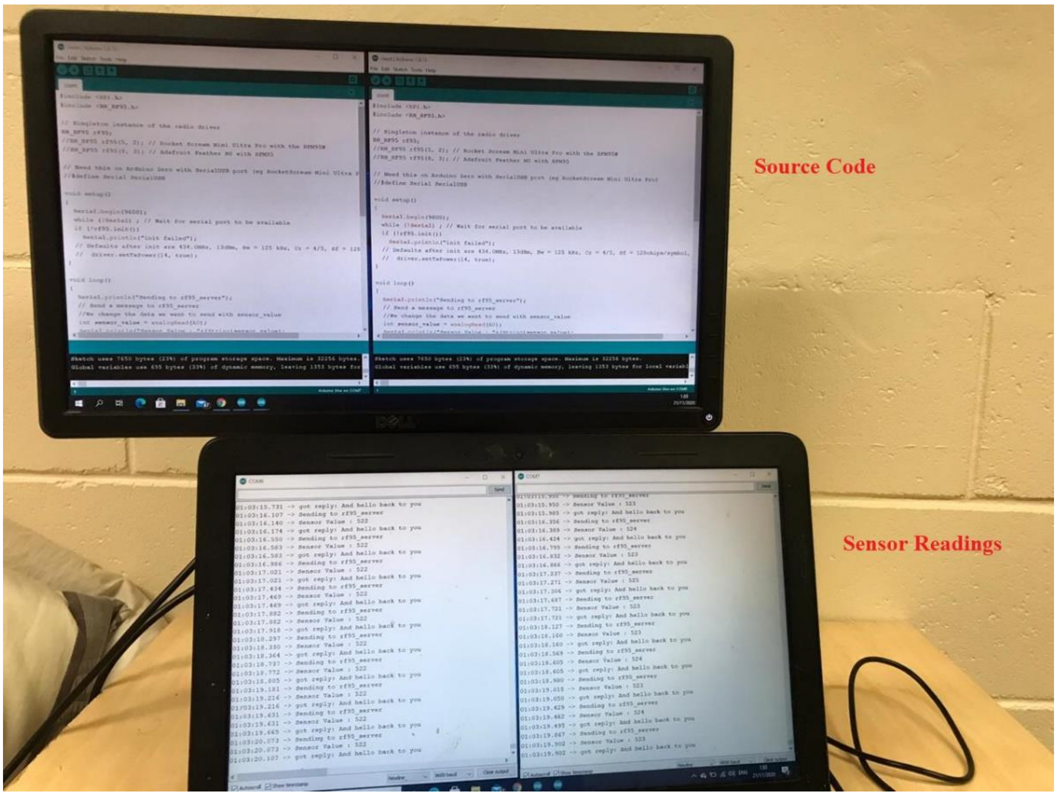

Figure 4.22. Receiving sensor data via LoRa communication channel

In a nutshell, LoRa technology can be used for agricultural applications because of lower latency, low power consumption, long-range, and long battery life.

5 Conclusion

5.1 Summary

Agriculture is an indispensable part of human life as it is the primary source of food, but it is essential to monitor the crops' quality and productivity. For instance, a sustainable environment should be provided for agriculture using smart technology for crop monitoring, smart irrigation, soil moisture monitoring, etc. Smart agriculture can be defined as a process where various sensors are integrated with communication technologies to monitor the changes in the environment due to various external factors, and collected data is optimized to make a smart decision. Soil moisture analysis is critical for the quality of the crop as soil acts as an important part of earthly water dynamics by maintaining precipitation on the ground. But the problem is the availability of affordable soil moisture sensors. Sensors previously available on the market have been too costly for many farmers in emerging countries. Affordable moisture measuring equipment can help mitigate this problem, and farmers can do precision farming with the help of the latest technologies.

This thesis's first aim was to perform a comparative analysis of different commercial off-the-shelf soil moisture sensors in terms of cost, accuracy, durability, and corrosion resistance. The second main goal is to find a feasible communication technology (LoRa and NB-IoT) for the considered scenario. With these aims, the author has investigated the cost-effective soil moisture sensors by considering four sensors by investigating freely available COTS sensors from different manufacturers and integrating the sensor with suitable communication technology for long-distance communication.

For experimental results, the author has chosen four sensors: Capacitive V1.0, Capacitive V1.2, Resistive (SEN0114) sensor, and Resistive (Grove) sensor. These sensors are tested with three different soils such as clay, loam, and silt soil for three different temperatures i.e., room temperature, 40^{o}C, and 50^{o}C. Capacitive V1.0 sensor behaves correctly according to the clay soil properties, i.e., it consists of small particles and has water retention properties. It shows the dry states for less water content (25% and 50%), but it only indicates wet and watery with more water content (75% and 100%) because clay soil absorbs the water and becomes sticky. Capacitive V1.2 sensor shows more deviation from the actual values with clay soil compared to Capacitive V1.0. Resistive sensors are less accurate compared to the capacitive sensors with clay soil.

Similarly, capacitive sensors show approximately the same behavior. Their readings revolve around the wet state at three temperatures, i.e., loam soil absorbs water quickly and drains easily. Again, Capacitive V1.2 has shown more deviation with loam soil as compared to Capacitive V1.0. However, it was tough to understand the resistive (SEN0114) sensor's behavior with loam soil because it reads nearly dry states for 25% water content. Still, it behaves unexpectedly for 50% water content as it reads wet state for higher temperature. The capacitive sensors also read the wet conditions for all the moisture content with little variation because silt soil has medium water-retention property. The sensor reading lies in the wet state range but shows a different trend for 100% water content. The resistive sensor has shown different behavior for all the moisture content levels, making it inaccurate because it is hard to understand how it behaves in silt soil. Overall, it can be concluded that the Capacitive V1.0 sensor is more accurate because it maintains the same behavior for all the water content levels as compare to Capacitive V1.2, Resistive (SEN0114), and Resistive (Grove) sensor.

Based on the comparative analysis of NB-IoT and LoRa technology, the author has found that LoRa technology can be used for agricultural applications because of lower latency, low power consumption, long-range, and long battery life.

Capacitive V1.0 sensor is most accurate, corrosion-resistant, and most durable among all the sensors, whereas capacitive V1.2 is less accurate than V1.0, but it is also corrosion-resistant, most durable, and cheaper. There is a trade-off between accuracy and cost. Capacitive V1.0 is costly than V1.2 but has more accuracy, while V1.2 is less expensive than V1.0 but has less accuracy. So, both can be used for agricultural applications based on the requirements such as accuracy or cost. On the other hand, as mentioned, resistive sensors are less accurate, corrode quickly, costly, and less durable.

Based on these results, it can be concluded that the thesis's initial purpose has been accomplished, i.e., comparative analysis of different COTS soil moisture sensors with a key figure of merits such as cost, accuracy, durability, corrosion resistance. And finally, feasible communication technology was investigated for long-range communication.

The results are encouraging and pave the way for the use of COTS sensors, mainly Capacitive V1.0 and Capacitive V1.2 soil moisture sensing for agriculture applications.

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Appendix 2 - Source Code

1. Source code for both V1.0 and V1.2 Capacitive sensor

```
void setup() {
  Serial.begin(9600); // open serial port, set the baud rate as 9600 bps
}
void loop() {
  int val;
  val = analogRead(0); //connect sensor to Analog 0
  Serial.println(val); //print the value to serial port
  delay(100);
}
```

2. Source code for DFRobot Sensor (Resistive, Grove sensor)

```
  # the sensor value description
  # 0  ~300     dry soil
  # 300~700     humid soil
  # 700~950     in water
*/

void setup(){

  Serial.begin(57600);

}

void loop(){

  Serial.print("Moisture Sensor Value:");
  Serial.println(analogRead(A0));
  delay(100);

}
```

3. Source code for the SEN0114

```
/* Change these values based on your calibration values */
#define soilWet 500   // Define max value we consider soil 'wet'
#define soilDry 750   // Define min value we consider soil 'dry'

// Sensor pins
#define sensorPower 7
#define sensorPin A0

void setup() {
	pinMode(sensorPower, OUTPUT);

	// Initially keep the sensor OFF
	digitalWrite(sensorPower, LOW);

	Serial.begin(9600);
}

void loop() {
	//get the reading from the function below and print it
	int moisture = readSensor();
	Serial.print("Analog Output: ");
	Serial.println(moisture);

	// Determine status of our soil
	if (moisture < soilWet) {
		Serial.println("Status: Soil is too wet");
	} else if (moisture >= soilWet && moisture < soilDry) {
		Serial.println("Status: Soil moisture is perfect");
	} else {
		Serial.println("Status: Soil is too dry - time to water!");
	}

	delay(1000);	// Take a reading every second for testing
					// Normally you should take reading
perhaps once or twice a day
	Serial.println();
}

//  This function returns the analog soil moisture measurement
int readSensor() {
	digitalWrite(sensorPower, HIGH);	// Turn the sensor ON
	delay(10);							//
Allow power to settle
	int val = analogRead(sensorPin);	// Read the analog value form
sensor
	digitalWrite(sensorPower, LOW);		// Turn the sensor OFF
	return val;							//
Return analog moisture value
}}
```

4. Source code for LORA client

```
#include <SPI.h>
#include <RH_RF95.h>

// Singleton instance of the radio driver
RH_RF95 rf95;
//RH_RF95 rf95(5, 2); // Rocket Scream Mini Ultra Pro with the RFM95W
//RH_RF95 rf95(8, 3); // Adafruit Feather M0 with RFM95

// Need this on Arduino Zero with SerialUSB port (eg RocketScream Mini
Ultra Pro)
//#define Serial SerialUSB

void setup()
{
  Serial.begin(9600);
  while (!Serial) ; // Wait for serial port to be available
  if (!rf95.init())
    Serial.println("init failed");
  // Defaults after init are 434.0MHz, 13dBm, Bw = 125 kHz, Cr = 4/5, Sf
= 128chips/symbol, CRC on
  //  driver.setTxPower(14, true);
}

void loop()
{
  Serial.println("Sending to rf95_server");
  // Send a message to rf95_server
  uint8_t data[] = "Hello I'm from lora!";
  rf95.send(data, sizeof(data));

  rf95.waitPacketSent();
  // Now wait for a reply
  uint8_t buf[RH_RF95_MAX_MESSAGE_LEN];
  uint8_t len = sizeof(buf);

  if (rf95.waitAvailableTimeout(3000))
  {
    // Should be a reply message for us now
    if (rf95.recv(buf, &len))
    {
      Serial.print("got reply: ");
      Serial.println((char*)buf);
    }
    else
    {
      Serial.println("recv failed");
    }
  }
  else
  {
    Serial.println("No reply, is rf95_server running?");
  }
  delay(400);
```

```
}
```

5. **Source code for the Lora (SERVER)**

```
#include <SPI.h>
#include <RH_RF95.h>

// Singleton instance of the radio driver
RH_RF95 rf95;
//RH_RF95 rf95(5, 2); // Rocket Scream Mini Ultra Pro with the RFM95W
//RH_RF95 rf95(8, 3); // Adafruit Feather M0 with RFM95

// Need this on Arduino Zero with SerialUSB port (eg RocketScream Mini
Ultra Pro)
//#define Serial SerialUSB

int led = 13;

void setup()
{
  // Rocket Scream Mini Ultra Pro with the RFM95W only:
  // Ensure serial flash is not interfering with radio communication on
SPI bus
//  pinMode(4, OUTPUT);
//  digitalWrite(4, HIGH);

  pinMode(led, OUTPUT);
  Serial.begin(9600);
  while (!Serial) ; // Wait for serial port to be available
  if (!rf95.init())
    Serial.println("init failed");
  // Defaults after init are 434.0MHz, 13dBm, Bw = 125 kHz, Cr = 4/5, Sf
= 128chips/symbol, CRC on

  // The default transmitter power is 13dBm, using PA_BOOST.
  // If you are using RFM95/96/97/98 modules which uses the PA_BOOST
transmitter pin, then
  // you can set transmitter powers from 5 to 23 dBm:
//  driver.setTxPower(23, false);
  // If you are using Modtronix inAir4 or inAir9,or any other module
which uses the
  // transmitter RFO pins and not the PA_BOOST pins
  // then you can configure the power transmitter power for -1 to 14 dBm
and with useRFO true.
  // Failure to do that will result in extremely low transmit powers.
//  driver.setTxPower(14, true);
}

void loop()
{
  if (rf95.available())
  {
    // Should be a message for us now
    uint8_t buf[RH_RF95_MAX_MESSAGE_LEN];
```

```
    uint8_t len = sizeof(buf);
    if (rf95.recv(buf, &len))
    {
      digitalWrite(led, HIGH);
//      RH_RF95::printBuffer("request: ", buf, len);
      Serial.print("got request: ");
      Serial.println((char*)buf);
//      Serial.print("RSSI: ");
//      Serial.println(rf95.lastRssi(), DEC);

      // Send a reply
      uint8_t data[] = "And hello back to you";
      rf95.send(data, sizeof(data));
      rf95.waitPacketSent();
      Serial.println("Sent a reply");
       digitalWrite(led, LOW);
    }
    else
    {
      Serial.println("recv failed");
    }
  }
}
```

6. Send integer sensor data over long range :

```
#include <SPI.h>
#include <RH_RF95.h>

// Singleton instance of the radio driver
RH_RF95 rf95;
//RH_RF95 rf95(5, 2); // Rocket Scream Mini Ultra Pro with the RFM95W
//RH_RF95 rf95(8, 3); // Adafruit Feather M0 with RFM95

// Need this on Arduino Zero with SerialUSB port (eg RocketScream Mini
Ultra Pro)
//#define Serial SerialUSB

void setup()
{
  Serial.begin(9600);
  while (!Serial) ; // Wait for serial port to be available
  if (!rf95.init())
    Serial.println("init failed");
  // Defaults after init are 434.0MHz, 13dBm, Bw = 125 kHz, Cr = 4/5, Sf
= 128chips/symbol, CRC on
  //  driver.setTxPower(14, true);
}

void loop()
{
  Serial.println("Sending to rf95_server");
  // Send a message to rf95_server
  //We change the data we want to send with sensor_value
```

```
  int sensor_value = analogRead(A0);
  Serial.println("Sensor Value : "+(String)sensor_value);
  char data[3];
  itoa(sensor_value, data, 10);
  rf95.send(data, sizeof(data))
  rf95.waitPacketSent();
  // Now wait for a reply
  uint8_t buf[RH_RF95_MAX_MESSAGE_LEN];
  uint8_t len = sizeof(buf);

  if (rf95.waitAvailableTimeout(3000))
  {
    // Should be a reply message for us now
    if (rf95.recv(buf, &len))
    {
      Serial.print("got reply: ");
      Serial.println((char*)buf);
    }
    else
    {
      Serial.println("recv failed");
    }
  }
  else
  {
    Serial.println("No reply, is rf95_server running?");
  }
  delay(400);
}
```