Cape Peninsula
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DESIGN AND IMPLEMENTATION OF CROP MONITORING AND IRRIGATION SYSTEM USING IoT AND CLOUD COMPUTING

by

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DECLARATION

I, Adamou Bello, declare that the contents of this dissertation represent my unaided work, and that the dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

October 2024

Signed **Date**

ABSTRACT

Farmers are under great strain due to the world's expanding population and increased awareness of the environmental demands that agriculture makes on the environment. They must increase yields to feed more people while also ensuring that their techniques are sustainable. A balance between intense production and environmental care is required, which cannot be accomplished within the limitations of traditional farming. For this reason, many are turning to The Internet of Things (IoT).

The integration of IoT and Cloud Computing, facilitated by Long Range (LoRa) and Long Range Wide Area Network (LoRaWAN) technologies, has emerged as a transformative force in the field of agriculture. This research explores designing, developing, and validating a Crop Monitoring and Irrigation System that seamlessly integrates IoT devices, cloud computing capabilities, and user-friendly interfaces. The system empowers farmers with real-time insights into soil conditions, crop health, and personalised recommendations for irrigation.

A comprehensive methodology was employed to achieve this, incorporating various engineering tools and software. The development and testing processes utilised Tera Term for terminal emulation, STM32CubeIDE 1.13.1 and STM32CubeMX for microcontroller configuration and programming, and draw.io for system design and documentation. PyCharm Community Edition 2023.2.1 was used for Python development, while STM32CubeMonitor facilitated real-time data monitoring. Postman API Platform was employed for API testing, and Node-Red was used for flow-based development. Both Python and C programming languages were integral to the system's development.

Through rigorous testing and validation, the operational success of the system is confirmed, ensuring reliable data availability on both the Loriot platform and user applications. The study contributes to the advancement of smart agriculture and presents implications for scientific research, providing a valuable resource for the study of crop characteristics and regional phenomena. Despite certain limitations, the system showcases potential for continuous innovation and adaptation to evolving agricultural needs.

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DEDICATION

This thesis is dedicated to my wife and children, whose love, support, and encouragement have been my greatest source of strength throughout this journey. Your unwavering belief in me has made this achievement possible.

I also dedicate this work to my late mother Moutango Catherine, my late sister Yakona Annick Stephanie, and finally, to my two lovely sisters, Bello Zenabou Abou and Ngalla Yvette, who instilled in me the value of education and perseverance. Your sacrifices and guidance have shaped the person I am today.

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ABBREVIATIONS

ABP:	Activation by Personalisation
ADR:	Adaptive Data Rate
AES:	Advanced Encryption Standard
AMQP	Advanced Message Queuing Protocol
AppSKey:	Application Session Key
BW:	Bandwidth
Chirp	Compressed High-Intensity Radar Pulse
CoAP	Constrained Application Protocol
CR:	Coding Rate
CRC:	Cyclic Redundancy Check
CSS	Chirp Spread Spectrum
FCntUp:	Frame counter uplink
FEC:	Forward Error Correction
FEM:	Finite Element Modelling
FPort:	Frame port
HTTP	Hypertext Transfer Protocol
IoT:	Internet of Things
ISM	Industrial, Scientific, and Medical
LPWAN:	Low Power Wide Area Network
LoRa:	Long Range
MCU:	Microcontroller
MHDR:	MAC Header
MIC:	Message Integrity Code
MQTT	Message Queuing Telemetry Transport
NwkSKey:	Network Session Key
OTAA:	Over-the-air Activation
Rs:	Symbol rate
SDG:	Sustainable Development Goal
SF:	Spreading factor
ToA:	Time on Air
TDR:	Time-domain reflectometry
UI:	User Interface
VWC:	Volumetric Water Content

CHAPTER ONE
INTRODUCTION

1.1 Introduction

As agriculture adapts to the demands of the 21st century, harnessing the power of cutting-edge technologies has become imperative to address the evolving challenges farmers face. The global agricultural landscape is experiencing unprecedented pressures due to climate change, population growth, and the need for sustainable practices. Traditional farming methods, while foundational, often fall short of meeting these modern demands. Consequently, there is a pressing need for innovative solutions that can enhance efficiency, productivity, and sustainability in agriculture.
The utilisation of advanced technologies such as the Internet of Things (IoT) and Cloud Computing has the potential to significantly transform the way agricultural activities are carried out. By employing sensor-equipped devices and cloud-based data processing, the proposed system aims to provide real-time monitoring and analysis of crop conditions, soil moisture levels, and environmental parameters. This empowers farmers with actionable insights to optimise irrigation strategies, improve resource allocation, and ultimately enhance crop yields while minimising water and energy usage.

The convergence of the IoT and Cloud Computing emerges as a transformative force, potentially revolutionising conventional farming practices. IoT technology enables the collection of vast amounts of data from various sensors distributed throughout the farm. These sensors can monitor soil moisture levels and temperature in real-time. Meanwhile, Cloud Computing offers robust platforms for storing, processing, and analysing this data, providing valuable insights and facilitating informed decision-making.

This research embarks on a journey to design and implement a CROP MONITORING AND IRRIGATION SYSTEM that seamlessly integrates IoT and Cloud Computing technologies. The primary goal of this system is to enhance resource utilisation and crop management, thereby contributing to more sustainable agricultural practices. By utilising real-time data and advanced analytics, the proposed system seeks to optimise irrigation schedules, reduce water wastage, and improve crop yields.

Ultimately, this research aims to link farming practices with contemporary technological innovations. By demonstrating the practical applications and benefits of IoT and Cloud Computing in crop monitoring and irrigation, this study aims to contribute to the broader adoption of smart agriculture practices.

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1.2 Background to the research

Climate change and water scarcity are pressing realities that significantly impact agriculture (Water and Climate Change, 2020). The agricultural sector is one of the largest consumers of water globally, with substantial amounts often lost through inefficient irrigation practices such as leaky channels and overwatering. These inefficiencies not only reduce crop yields but also contribute to the depletion of valuable water resources. Moreover, different crops have varying water requirements, necessitating precise water management techniques to ensure optimal growth and productivity (Biradar and Shabadi, 2017).

Effective water management in agriculture is critical to addressing these challenges. Traditional methods often fall short of providing the necessary precision and efficiency. Consequently, there is a growing interest in adopting advanced technologies such as IoT to enhance agricultural practices. IoT solutions in agriculture typically involve deploying sensors connected to the internet to collect environmental data. These sensors provide farmers with the ability to monitor their fields remotely, offering a level of oversight and control previously unattainable.

The use of IoT in agriculture allows for continuous, real-time monitoring of various parameters such as soil moisture levels and temperature. This data is accessible from any connected device, enabling farmers to make informed decisions quickly. The flexibility of IoT systems allows for both manual and automated responses to the collected data, facilitating critical data-driven activities that can improve efficiency and crop management. Additionally, IoT sensors are designed for durability and longevity, capable of gathering data for extended periods without requiring frequent maintenance or replacement.

One of the primary advantages of IoT in agriculture is the provision of real-time insights into soil and environmental conditions. This capability empowers farmers to react promptly to changes, optimising irrigation and other agricultural practices based on accurate and current data. Mobile and desktop applications further enhance this capability by providing a user-friendly interface for data analysis and decision-making. According to Navarro, Costa, and Pereira (2020), crop monitoring and irrigation control are among the most popular applications of IoT solutions in smart farming. Crop monitoring involves tracking soil moisture and temperature to ensure optimal growing conditions for crops. By precisely monitoring these parameters, IoT-enabled systems can adjust watering schedules and amounts to meet the specific needs of different crops. This targeted approach not only conserves water but also enhances crop health and productivity by preventing over- or under-watering.

Irrigation control, another crucial application, leverages IoT data to optimise water usage. By precisely monitoring soil moisture levels and weather conditions, IoT-enabled irrigation systems can adjust watering schedules and amounts to meet the specific needs of different crops. This targeted approach not only conserves water but also enhances crop health and productivity by preventing over- or under-watering. Furthermore, IoT technology can integrate with other advanced systems, creating a comprehensive smart farming ecosystem. This integration facilitates a more holistic view of the farm, enabling better resource management and strategic planning.

The integration of IoT in agriculture represents a significant advancement in addressing the challenges posed by climate change and water scarcity. By providing real-time data and actionable insights, IoT technologies empower farmers to optimise their practices, conserve resources, and improve crop yields. The adoption of IoT in smart farming is a testament to the potential of technological innovation to transform traditional agricultural practices and promote sustainability in the sector.

1.3 Research Problem Statement

Poor irrigation management can irrevocably harm crop quality and growth, increasing the possibility of yield reduction and financial loss for farmers. Furthermore, the growing difficulties of water management and climate change necessitate more effective and tailored systems for detecting water levels, measuring soil moisture, and managing correct irrigation in real time to prevent water damage, decrease scheduled manual operations, and reduce water loss.

1.4 Significance of the research

Sustainable Development Goal (SDG) 2 seeks to eliminate all kinds of hunger and malnutrition by 2030, ensuring that all people, particularly the most vulnerable and poorest, have access to sufficient and nutritious food all year round (United Nations Development Programme, 2021). According to the United Nations, the world’s population will reach 9.7 billion by 2050 (Verenigde Naties, 2019), to feed this enormous population, food production must grow by 70% (FAO, 2009), and that puts a lot of pressure on farmers and agricultural companies to meet this demand and at the same time, they are under tremendous pressure to conserve water. The usage of IoT in agriculture will play a key part in this problem. The market share for IoT in agriculture is estimated to have a revenue of $10 billion in 2030 (Navarro, Costa and Pereira, 2020).

1.5 Research questions

This research addressed several key research questions, including how to protect personal information and agricultural data against cyber-attacks, how to minimise interference between multiple IoT devices, how to optimise data sampling methods to minimise power consumption, how to enable farmers to interact with the system in areas with limited internet connectivity, and how to manage data transfer and storage in areas with limited bandwidth and high internet access costs.

1.6 Aim and Objectives

This research aims to develop an integrated IoT and cloud computing platform that can help prevent water loss, optimise crop growth, and maximise production for farmers of all income levels.

The main objective is to design and develop a fully functional prototype that integrates diverse types of networks into a single IoT platform that can be scaled to serve different types of farmers efficiently. The second objective is to develop a user-friendly mobile application and desktop application that will allow farmers to access real-time insights into soil conditions and crop health.

To achieve the objectives stated above, the following tasks were undertaken:

- To write a literature review on the current state of IoT and cloud computing technologies in smart agriculture.
- To model the system architecture of the Smart Agriculture System.
- To apply best practices in IoT and cloud computing integration for agricultural applications.
- To develop an algorithm for optimising irrigation schedules based on real-time sensor data.
- To model and simulate the case study network in a suitable software environment, such as Cisco Packet Tracer
- To configure and test the IoT devices and ensure seamless data transmission to the cloud.
- To implement edge-level decision-making capabilities for autonomous irrigation control.
- To validate the system through extensive field testing and user interaction analysis.
- To analyse the collected data and provide actionable insights for improving agricultural practices.

1.7 Research design and methodology

The primary goal of the Internet of Things is to gather information using sensors and then save and analyse this information, either locally in the Fog/Edge network using microcontrollers or microcomputers or remotely using Cloud computing.

To properly design the system, the following steps must be carried out to select key components, leading to the final system architecture.

1.7.1 Sensors

To choose appropriate sensors few things must be considered and among them are:

- Durability and stability
- Power consumption
- Connection range:
- Cost
- Precision and reliability

1.7.2 Network technologies and protocols

The following criteria are used in identifying the best technologies and protocols to be used.

- Coverage
- Bandwidth
- Power consumption
- Cost

1.7.3 Storage and Processing

The raw data acquired by sensors must be saved and processed to be transmitted into meaningful information that can be used to make intelligent decisions.

- In remote and rural areas data is saved and processed at the fog/edge.
- In urban areas, data is saved and processed at cloud levels.

1.7.4 Microcontrollers or Microcomputers

The selection is based on the following criteria.

- Peripheral sensors and output components
- Data communication and protocols
- Networking hardware and protocols
- Bare-metal or operating system

1.7.5 Security requirements

- Methodologies for authentication and control of upstream communications
- Ability to remotely upgrade drivers and firmware.

1.7.6 Low power consumption

- Technics such as low sampling rates and transmission periods can be utilised to minimise energy usage.
- Computation can be pushed as close to the edge as feasible so that all processing can be done at that level, and only critical data is then sent out to the Cloud for further processing.

1.7.7 Mobile and Desktop Application Development

The development process entails the creation of intuitive desktop and mobile applications that provide farmers with real-time data visualisation of moisture levels, battery levels, and temperature, alongside access to historical data, and manual control over the irrigation system. This enhances user engagement and decision-making capabilities.

1.8 Expected outcomes

The following results were realised by the conclusion of the thesis:

- A fully scalable functional prototype that can be deployed in remote rural areas and urban areas.
- Mobile application
- Desktop application

1.9 Contributions of the research

The research will help to alleviate some of the challenges that African farmers in remote and rural areas face. It will take into consideration the internet access problem, which is either unavailable or prohibitively expensive.

1.10 Organisation of the Thesis

The structure of the dissertation/thesis consists of six chapters, the details of what each chapter entails are as follows:

1.10.1 Chapter One

This chapter is the overall introduction of the research, where the study's background is described, highlighting the purpose, the aim and objective, and the whole dissertation structure.

1.10.2 Chapter Two

This chapter entails the literature reviewed concerning this study, the latest developments, and the research gaps identified relating to this research.

1.10.3 Chapter Three

The third chapter presents the theory applicable to the research study to achieve the research objectives through the methodology proposed in Chapter One.

1.10.4 Chapter Four

This chapter describes the research methodology used in this study, including the design of the IoT platform and the methods used to evaluate its performance.

1.10.5 Chapter Five

This chapter presents the outcomes of system validation tests and data availability assessments

1.10.6 Chapter Six

This chapter discusses the conclusions and implications of this research, including its potential impact on the agriculture industry and future research directions.

1.11 Summary

This introductory chapter sets the stage for the thesis, "Design and Implementation of Crop Monitoring and Irrigation System Using IoT and Cloud Computing." It begins with a background that underscores the importance of integrating IoT with cloud computing to enhance agricultural practices through advanced crop monitoring and automated irrigation solutions. The research problem statement identifies the key challenges faced in achieving efficient and secure agricultural data management and device operation in such systems. The significance of the research is articulated through its potential to revolutionise farming techniques, improve water resource management, and increase crop yields while ensuring data security and system reliability. The research questions aim, and objectives are precisely defined to direct the development of a robust IoT-based agricultural system. The methodology section describes the technical approach involving sensors, network protocols, microcontrollers, and cloud storage solutions tailored to agricultural needs. Security requirements and low power consumption strategies are emphasised as critical to sustainable system design. The expected outcomes and the anticipated contributions of the research are also detailed, highlighting the expected advancements in agricultural technology and practices.

This chapter sets the foundation for a thorough exploration of the IoT, and cloud computing technologies detailed in the subsequent chapters.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

The literature review for this research was conducted to establish a comprehensive understanding of the current state of IoT and cloud computing technologies in the context of IoT-based agricultural systems. The primary aim was to identify existing solutions, highlight gaps in the current knowledge, and set the foundation for developing a robust IoT-based agricultural system. The literature review process involved several key steps:

The first step involved clearly defining the scope and objectives of the literature review. The focus was on IoT and cloud computing applications in agriculture, particularly concerning resource optimisation, crop management, and data analytics.

The objectives were to:

- Identify key technologies and methodologies currently being used.
- Understand the challenges and limitations of existing systems.
- Highlight the latest advancements and emerging trends in the field.
- Identify gaps in the current research that this study could address.

The second step involved A comprehensive literature search using several academic databases and search engines, including:

- **IEEE Xplore:** For papers related to IoT technologies and applications.
- **ScienceDirect and Elsevier**: To access journal articles on cloud computing and smart agriculture.
- **Google Scholar:** For a broad search of academic publications and patents.
- **Web of Science:** For high-impact research articles and reviews.
- **MDPI:** For multidisciplinary research articles, including those on IoT and cloud computing in agriculture.
- **ResearchGate:** For accessing a wide range of research articles.

Keywords and phrases used in the search included "IoT in agriculture," "cloud computing in agriculture," "smart farming technologies," "precision agriculture," "IoT sensor networks," "agricultural data analytics," and "resource optimisation in farming." The last step involved the selection of relevant literature based on the following criteria:

- **Relevance:** Papers that specifically addressed IoT and cloud computing in agriculture.
- **Recency:** Focus on studies published within the last 10 years to ensure the inclusion of the most current research and technological advancements.
- **Impact:** Preference for high-impact journals and conferences

2.2 Detailed Review of Selected Papers

This section comprehensively reviews the literature on Internet of Things technologies employed in agriculture. Table 2.1 compiles key studies, outlines the technologies utilised, and summarises their principal findings to facilitate a structured comparison of the existing literature.

Table 2.1: Comparative Overview of IoT Technologies in Agriculture

Author	Year	Technologies Used	Focus Area	Title of Paper
Harleen et al.	2022	Cloud computing, ESP32, Node MCU, sensors, and RFID.	IoT technologies and their application in agriculture	Review of IoT Technologies Used in Agriculture
Debauche et al.	2022	Cloud and distributed computing architectures	Data Management Challenges in Agriculture 4.0	Cloud and Distributed Architectures for Data Management in Agriculture 4.0: Review and Future Trends
Pathmudi et al.	2023	Sensors, controllers, and communication standards used	IoT technologies in agriculture	A Systematic Review of IoT Technologies and Their Constituents for Smart and Sustainable Agriculture Applications
Pagano et al.	2023	LoRa and LoRaWAN	LoRa and LPWAN technology in smart agriculture	A Survey on LoRa for Smart Agriculture: Current Trends and Future Perspectives

Kaur, Shukla and Singh (2022) presented a thorough review of IoT technologies in agriculture, highlighting the impact of modern technologies on monitoring and control practices. The paper discusses the use of IoT in key areas such as irrigation management, soil and water quality monitoring, and pest and disease control. These IoT applications significantly improve agricultural productivity and address challenges like water scarcity and soil nutrient depletion by integrating sensors and communication technologies. The authors conducted a comprehensive literature review identifying and discussing IoT technologies used in various agricultural applications. They organised the studies into a table, detailing technologies such as cloud computing, sensors, and RFID. The review also explained multi-layer IoT frameworks that enable efficient data collection, communication, and analysis.

Debauche et al. (2022) explored the critical data management challenges in Agriculture 4.0, focusing on the role of cloud and distributed computing architectures. The study classifies these architectures into four main types: central cloud, distributed cloud, collaborative computing strategies, and emerging trends; and discusses their uses in smart farming. The authors conducted a systematic literature review and developed eight criteria for comparing different computing architectures: user proximity, latency and jitter, network stability, high throughput, reliability, scalability, cost-effectiveness, and maintainability. The comparison includes cloud computing, fog computing, edge computing, lambda architecture, kappa architecture, and osmotic computing. The review highlights that no single architecture meets all the needs of Agriculture 4.0 due to diverse data types, volumes, and processing requirements. It identifies the following:

- **Central Cloud Architectures:** Suitable for batch processing and offline analysis but face latency issues in real-time applications.
- **Distributed Cloud Architectures:** Offer resilience and flexibility with multi-cloud and federated cloud approaches.
- **Collaborative Computing Strategies:** Combine fog and edge computing for better latency management but are resource limited.
- **Emerging Trends:** Hybrid architectures that merge cloud and edge/fog computing, balancing latency-sensitive operations with large-scale data analysis.

The paper also notes significant gaps in cross-compatibility, interoperability, and standardised protocols for data management. It suggests that future research should focus on developing these protocols and enhancing data security in collaborative and distributed architectures.

Pathmudi et al. (2023) presented a detailed review of IoT technologies in agriculture, emphasising how these technologies can improve the efficiency of agricultural operations and support sustainable practices. The review summarises findings from various studies, highlighting a shift from traditional farming to more data-driven and automated approaches. The authors conducted a systematic literature review examining IoT components such as sensors, controllers, and communication protocols that enhance agricultural productivity and sustainability. The study concludes that IoT technologies play a crucial role in automating farming and enabling precision agriculture, thereby optimising resource use, such as water and fertilisers, and increasing yields with minimal human intervention. Key challenges and future directions identified include improving the cost-effectiveness of IoT systems, enhancing data security, and developing interoperable technologies that can integrate seamlessly with different agricultural systems.

Pagano et al. (2023) provided a comprehensive survey on using LoRa technology within smart agriculture, a key component of low-power wide-area network (LPWAN) technologies. The survey analyses LoRa's application across various agricultural scenarios including irrigation systems, plantation and crop monitoring, tree monitoring, and livestock monitoring, discussing its scalability, interoperability, network architecture, and energy efficiency. The authors performed an extensive literature review focusing on four major application areas of LoRa technology in agriculture. They assessed the technical requirements, impacts, and challenges of LoRa-based systems, providing insights into recent advancements and foundational practices. The survey results indicate that LoRa holds great potential for the agriculture sector, mainly because of its extensive coverage, energy efficiency, and cost-effectiveness.

- **Irrigation Systems:** Using automated, data-driven controls, LoRa-based systems enhance water efficiency.
- **Plantation and Crop Monitoring:** Enables precise monitoring and resource management, reducing environmental impacts.
- **Tree Monitoring:** Provides connectivity in challenging environments, supporting health monitoring and stress detection in trees.
- **Livestock Monitoring**: Offers extended range monitoring crucial for large grazing fields, improving animal welfare and management.

The paper also identifies key areas for further research:

- **Energy Management**: Critical for improving the battery life of sensor nodes.
- **Downlink Latency:** Addresses the limitations in real-time control due to LoRa's downlink capabilities.
- **Device Heterogeneity and Scalability:** Calls for robust interoperability standards and enhanced network management strategies to support farm expansion.

2.3 Improved Resource Efficiency

This section explores the literature regarding IoT and related technologies in crop monitoring and irrigation management within agriculture. To provide a structured comparison of the reviewed literature, Table 2.2 compiles key studies, lists the technologies used, and outlines their principal findings.

Table 2.2: Key IoT Applications for Crop Monitoring and Irrigation Management

Author	Year	Technologies Used	Focus Area	Title of Paper
Rajalakshmi et al.	2016	Arduino microcontroller, Zigbee and GSM/GPRS modem JSON, DHT11, soil moisture sensor	Crop monitoring and irrigation	IoT-based crop-field monitoring and irrigation automation
Nageswara et al.	2018	Raspberry PI 3, soil moisture and temperature sensors, cloud computing	Crop monitoring and irrigation system	IoT-based smart crop field monitoring and automation irrigation system
Singh et al,	2019	Arduino Uno Sensors (FC-28, TMP-36) Wi-Fi module (ESP8266), cloud	Smart irrigation system	IoT Based Approach for Smart Irrigation System Suited to Multiple Crop Cultivation
Vij et al.	2020	ESP8266 microcontroller, DHT11, WI-FI, Raspberry PI 3, GSM and Bluetooth modules	IoT and Machine learning	IoT and Machine Learning Approaches for Automation of Farm Irrigation System
Viswanatha et al.	2022	ESP32S microcontroller, DHT 11, MQTT	Smart agriculture system	Implementation of IoT in

		protocol, Arduino IoT cloud platform		Agriculture: A Scientific Approach for Smart Irrigation
Placidi et al.	2022	Capacitive soil moisture measurement	Soil moisture measurement for precision agriculture	Capacitive Low-Cost System for Soil Water Content Measurement in the IoT Precision Agriculture
Ramachandran et al.	2022	sensors, controllers, hardware platforms, artificial neural networks, machine learning for irrigation, tools and software for irrigation management.	Irrigation management optimisation	Exploiting IoT and Its Enabled Technologies for Irrigation Needs in Agriculture

Ramachandran et al. (2022) discussed the use of the IoT and related technologies to improve irrigation in agriculture. They address how IoT can enhance irrigation management, the technologies and methodologies involved, and the challenges and future directions in this field. The study is based on previous research and focuses on advancements in sustainable water usage in agriculture since the 1970s. It provides a comprehensive review of literature and technology, examining the evolution of irrigation, factors affecting it, and technologies enabling optimisation. The paper offers an overview of IoT in agriculture, discussing commonly used sensors and controllers, hardware platforms, artificial neural networks, machine learning for irrigation, and tools and software for irrigation management. The paper concludes that IoT and related technologies can potentially improve irrigation management, emphasising the need to integrate sensors, cloud platforms, machine learning, and neural networks. It also highlights the need for agriculture-specific sensors, the development of soft sensors, and the importance of data for effective analysis in machine learning and neural network approaches. The paper suggests developing irrigation management tools with direct access to sensor data and the need for a complete framework for IoT in agriculture.

Placidi et al. (2022) introduced a cost-effective capacitive soil moisture measurement system tailored for precision agriculture. The system utilises capacitive sensor properties to measure soil volumetric water content (VWC) and salinity at the same time. It features a modified capacitive sensor paired with an AD5933 impedance converter to provide precise readings across a frequency range of 10 to 100 kHz. The study shows that this frequency range is well-suited for capacitive sensing in detecting soil water content, making it a comprehensive solution for smart irrigation. The system was calibrated using precision reference capacitors, and its results were compared against a high-precision laboratory LCR meter. The system was tested in both air and water to verify its accuracy. Finite Element Modelling (FEM) was used to simulate the sensor's electrical behaviour at different frequencies and water conductivities, providing insights into how the sensor's admittance correlates with these parameters. Additionally, the sensor's response was characterised under controlled laboratory conditions to establish its reliability and performance.

Viswanatha et al. (2022) investigated the implementation of IoT in agriculture, focusing on the development and application of a smart irrigation system. This system utilises a microcontroller to monitor environmental parameters such as soil moisture, temperature, and humidity, using this data to control irrigation through automated motor pumps. This approach aims to optimise water usage, ensuring crops receive the ideal amount of water and thus enhancing agricultural efficiency. The system uses an ESP32S microcontroller and sensors such as DHT11 for temperature and humidity, and a soil moisture sensor. The collected data is sent to the cloud via the MQTT protocol and is managed using the Arduino IoT cloud platform. This allows for remote monitoring and control of irrigation practices.

The prototype effectively controlled irrigation practices, adhering to critical temperature and humidity thresholds in regions like India. It adjusted irrigation based on real-time soil moisture conditions, reducing unnecessary water usage and aligning with sustainable farming practices. The authors used an IoT architecture of four layers (perception, network, management service, and application).

Nageswara et al. (2018) proposed IoT Based Smart Crop-Monitoring and Automation Irrigation System. The system uses a soil moisture sensor and a temperature sensor to collect data from the field. The collected data is then sent to the cloud via Raspberry Pi 3. The cloud then computes the required quantity for irrigation. The result is sent back to the Raspberry Pi 3which then drives the irrigation system based on the predefined threshold value. The farmer can access data via his mobile phone or a desktop computer. The system uses three layers of IoT architecture (perception, network, and application).

Singh et al. (2019) proposed IoT Based Approach for Smart Irrigation System Suited to Multiple Crop Cultivation. The proposed automated irrigation system appropriate for Indian farming practices uses IoT and data science to perform real-time analytics on the collected data. Two types of sensors a humidity sensor and a temperature sensor are positioned in the field to collect data that is then uploaded to the cloud system via WI-FI using Arduino Uno and ESP8266. The cloud system obtains the necessary data from the meteorological station and compares it to the data collected on-site. The analysis is then performed using data science technics to determine the quantity of water per crop type to be released in the field. The result is sent back to a Pump module which comprises Arduino Uno, a Wi-Fi module, and a Digital pump to release the required water. The system also includes a mobile application that allows the farmer to keep track of what is going on in the field. The authors used an IoT architecture of four layers (perception, network, management service, and application).

Rajalakshmi et al. (2016) proposed IoT-based crop-field monitoring and irrigation automation. The system uses a soil moisture sensor, temperature and humidity sensor, and a light-dependent resistor sensor which collects data uploaded to the web server via a wireless module. The transmitted data is in JSON format and stored in a database. When the temperature and moisture data fall below a threshold level, the irrigation system is switched on. When the moisture level is greater than the threshold value the irrigation system is switched off. Farmers receive notifications periodically via their mobile phones and can also monitor their farmer's state from anywhere. The authors used an IoT architecture of four layers (perception, network, management service, and application).

The article “IoT and Machine Learning Approaches for Automation of Farm Irrigation System” (Vij et al., 2020) This article explores the use of IoT and machine learning approaches for the automation of farm irrigation systems. The authors discuss the current state of farm irrigation systems, including their limitations and the potential benefits of automation. They then present a system architecture that utilises IoT sensors to collect environmental data and transmit the data to a central server using WI-FI communication. The data is then analysed using machine learning algorithms to determine the optimal time and amount of water to be applied to the crops. The authors also provide a detailed description of the components of their system and how they are integrated. Finally, they present experimental results that demonstrate the effectiveness of their system in improving water use efficiency and crop yield. The authors used an IoT architecture of four layers (perception, network, management service, and application).

2.4 Comparison of IoT Protocols for Smart Agriculture

In the context of IoT applications in smart agriculture, the choice of communication protocol plays a crucial role in determining the system's efficiency, reliability, and power consumption. Several IoT protocols have been developed to meet the varying needs of different IoT deployments. This section provides a comparative analysis of the most used IoT protocols, focusing on their application in smart agriculture. The comparison considers key criteria such as message size, overhead, latency, reliability, and overall suitability for agricultural applications.

2.4.1 MQTT (Message Queuing Telemetry Transport)

MQTT is a lightweight protocol that operates on a publish-subscribe model as shown in Figure 2.1, making it ideal for variable network reliability scenarios (MQTT, n.d). It is highly efficient in terms of bandwidth usage and power consumption (Sidna et al., 2020), which are critical in agriculture for real-time monitoring of environmental conditions such as soil moisture and temperature. However, its reliance on a broker introduces a single point of failure, which could be a limitation in large-scale deployments.

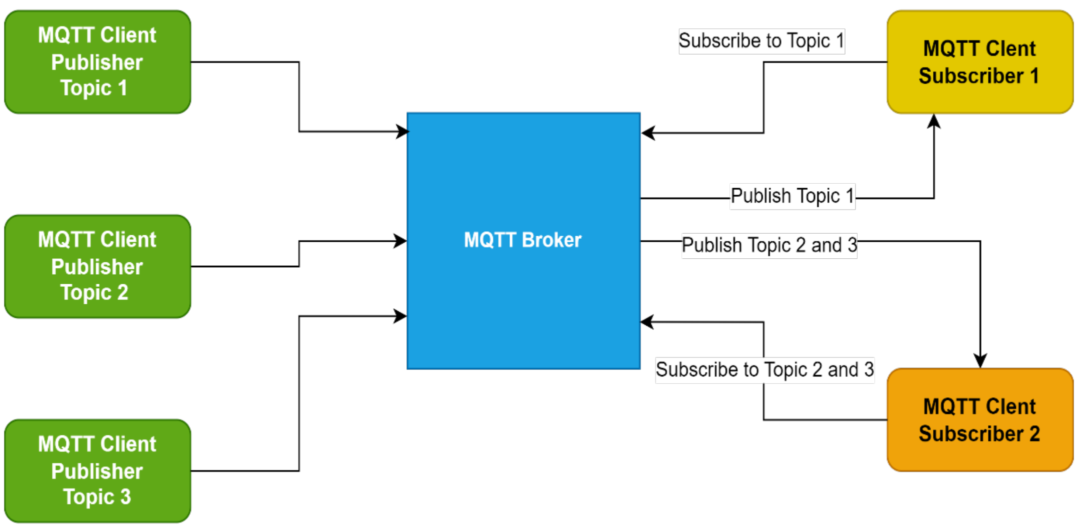

Figure 2.1: MQTT Architecture

2.4.2 CoAP (Constrained Application Protocol)

CoAP is designed specifically for use in constrained environments (Internet Engineering Task Force, n.d) such as those typical in agricultural IoT systems. It facilitates a request/response interaction model between application endpoints and operates over UDP, making it lightweight as shown in Figure 2.2. However, it may be less reliable than TCP-based protocols like MQTT (Moraes et al., 2019). CoAP's request/response model, which is similar to HTTP but with a smaller footprint, is well-suited for transmitting small amounts of data from distributed sensors.

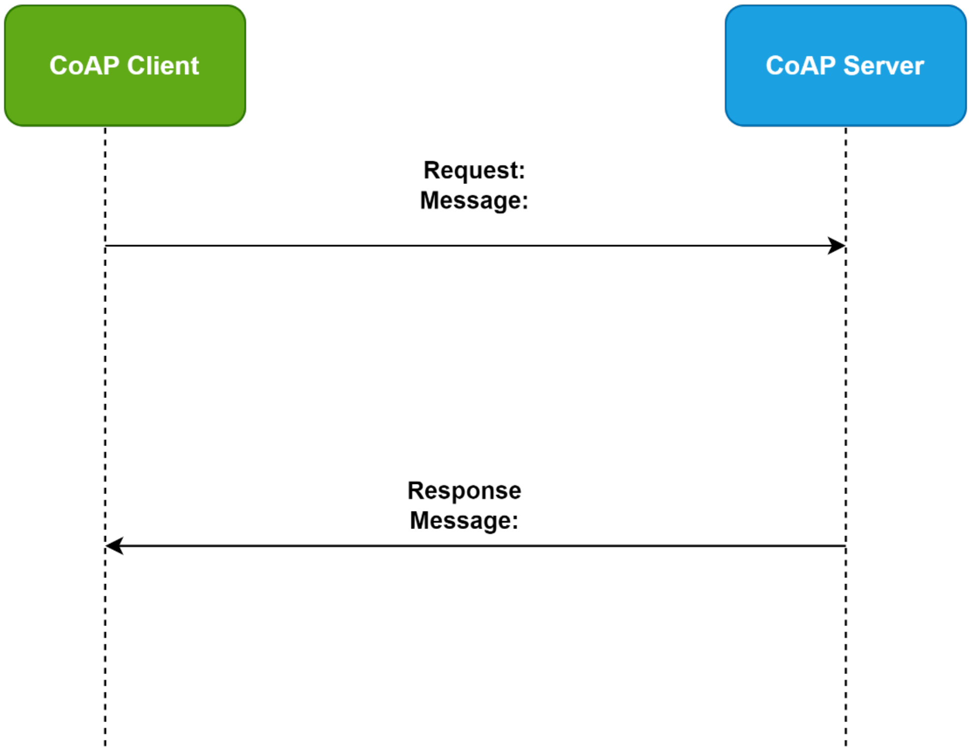

Figure 2.2: CoAP Architecture

2.4.3 HTTP (Hypertext Transfer Protocol)

HTTP is commonly used in web-based applications, but its overhead makes it less suitable for low-power IoT devices often used in agriculture. While it offers high reliability and is easy to implement, HTTP's bandwidth and energy consumption inefficiency (Sidna et al., 2020) limits its usability in scenarios where resources are limited.

2.4.4 AMQP (Advanced Message Queuing Protocol)

AMQP is a robust protocol designed for message-oriented middleware, providing features such as queuing, routing, and security (Bahashwan et al., 2019). As shown in Figure 2.3, the AMQP architecture includes key components like producers, exchanges, queues, and consumers, which ensure the reliable delivery of messages across a network. While it offers high reliability and interoperability, its complexity and overhead are drawbacks for resource-constrained agricultural IoT devices. AMQP might be more suitable for centralised systems where secure, reliable communication is critical.

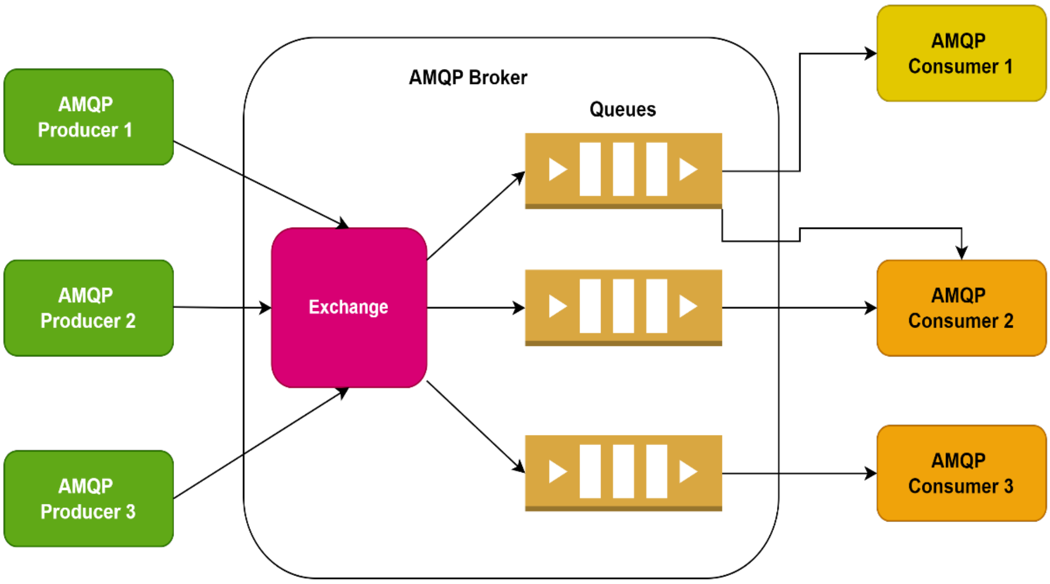

Figure 2.3: AMQP Architecture

2.4.5 WebSocket

WebSocket is well-suited for scenarios that necessitate real-time, two-way communication, offering low latency and moderate power consumption (Bahashwan et al., 2019). However, due to its continuous connection requirement, it may lead to higher power usage compared to MQTT and CoAP. As a result, it is more appropriate for real-time applications where immediate data exchange is crucial, such as remote machinery control or live data feeds.

2.4.6 Summary of Comparative Analysis

Figure 2.4 shows the comparative analysis highlights the varying strengths and limitations of each protocol. MQTT and CoAP demonstrate high efficiency in power consumption and low overhead, making them particularly suitable for constrained environments in smart agriculture. HTTP, although highly reliable, shows higher overhead and power consumption, which may limit its effectiveness for battery-powered devices in remote agricultural settings. AMQP, despite its robust security and reliability features, is less suitable for resource-constrained devices due to its complexity and overhead. On the other hand, WebSocket is ideal for real-time applications but may require more power than MQTT and CoAP.

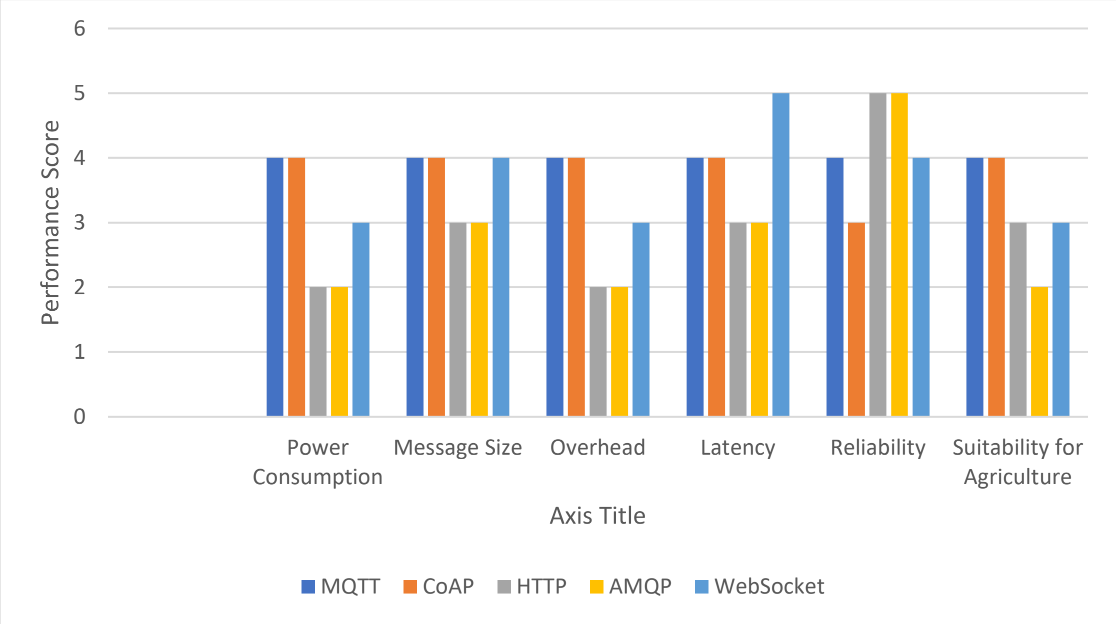

Figure 2.4: **Comparative Analysis of IoT Protocols for Smart Agriculture**

In Figure 2.4, each IoT protocol (MQTT, CoAP, HTTP, AMQP, and WebSocket) is evaluated across several key criteria that are critical for their application in smart agriculture. The numerical values assigned to each protocol range from 1 to 5, where:

- 1: Indicates the least favourable performance or suitability.
- 5: Indicates the most favourable performance or suitability.

These numbers are used to score each protocol on the following criteria:

- **Power Consumption:** Reflects the protocol's efficiency in terms of energy usage, crucial for battery-powered devices.
- **Message Size:** Indicates how well the protocol handles small data packets, typical in IoT sensor communication.
- **Overhead:** Assesses the protocol's efficiency in terms of additional data required to manage communication.
- **Latency:** Measures the time taken for data to be transmitted, important for real-time applications.
- **Reliability:** Evaluates the protocol's consistency and accuracy in data transmission.

- **Suitability for Agriculture:** A holistic score based on how well the protocol meets the specific needs of smart agriculture.

These criteria are represented on the X-axis of Figure 2.4, with the numerical scores plotted to visualise the performance of each protocol. Higher scores indicate better performance or greater suitability for that criterion, helping to compare and contrast the protocols effectively.

2.5 Summary

This literature review has critically examined the diverse applications and implications of IoT technologies in agriculture. Through an in-depth analysis of selected papers, this review has highlighted how IoT innovations are being integrated into various agricultural practices to enhance efficiency, productivity, and sustainability. IoT technologies, including sensor networks, cloud computing, and data analytics platforms, are transforming agriculture by providing precise and real-time monitoring of agricultural environments. Systems such as smart irrigation, soil moisture monitoring, and crop health assessment have been discussed, illustrating the practical and potential applications of IoT in agriculture. While IoT technologies offer substantial benefits, they also present significant challenges. Interoperability between different IoT systems, scalability of IoT solutions across varied agricultural settings, data security concerns, and the need for robust network infrastructure to handle the vast amounts of data generated are notable challenges. In evaluating some of the discussed papers, it is crucial to address the limitations associated with the use of standard wireless network sensors and Wi-Fi as the primary communication protocol. While wireless network sensors are commonly used, their feasibility in remote areas warrants further consideration, necessitating a closer examination of the specific challenges that may arise in these environments. Moreover, relying solely on Wi-Fi for communication imposes significant constraints, particularly in terms of signal range and power consumption. For instance, studies such as (Navarro, Costa and Pereira, 2020) have highlighted that Wi-Fi may not be suitable for larger projects and areas with power constraints, limiting its practicality. To enhance the applicability of these systems, it is imperative to go beyond passive monitoring. The current systems do not empower farmers to intervene proactively, transforming them from passive users into active participants. Considering the limitations mentioned, exploring alternative communication protocols or technologies that better align with the demands of remote areas and larger projects becomes crucial. This approach aims to foster a more dynamic and effective integration of technology in agriculture.

The review has identified several areas for further research. These include the development of more energy-efficient IoT devices, the use of advanced data analytics and machine learning for predictive agriculture, and the creation of more user-friendly interfaces for agricultural IoT systems. Enhancing the connectivity options to ensure reliable data transmission in rural areas is also a critical area for future development.

The findings from this literature review not only highlight the current capabilities of IoT in agriculture but also chart a course for future research and application, suggesting that the continued evolution and integration of IoT technologies will be crucial in meeting the growing global demands for food production and resource management.

CHAPTER THREE
THEORETICAL FRAMEWORK

3.1 Introduction

This chapter provides a theoretical framework for the development of an integrated IoT and cloud computing platform for smart agriculture. It explores the key concepts, principles, and theories that underpin the platform, including the use of sensors, processors, data storage, network technologies and protocols, and integration. By examining these elements in detail, this chapter aims to demonstrate the theoretical basis for the platform and its potential to reduce water loss, improve crop development, and maximize productivity for farmers of all income levels.

3.2 Sensors

Smart agriculture relies on the use of sensors to collect data on various environmental factors, including soil moisture, temperature, humidity, and light. These sensors can be categorised based on the physical properties they measure.

There are several types of soil moisture sensors available, including resistance, capacitance, time-domain reflectometry (TDR), and neutron probes. Each type of sensor has its benefits and drawbacks. However, in the realm of IoT-based soil moisture monitoring systems, capacitive and resistive sensors are widely favoured due to their affordability and ease of integration when compared to other sensor types (Chowdhury et al., 2022). Their low cost makes them an attractive choice, particularly for large-scale deployments or projects with budget limitations. Additionally, these sensors can be easily integrated into IoT systems, as they offer analog or digital output signals that seamlessly interface with microcontrollers or IoT platforms for efficient data collection and analysis. The widespread availability of capacitive and resistive sensors further contributes to their popularity in IoT-based soil moisture monitoring applications. While they may not provide the highest level of accuracy compared to more sophisticated sensors, these sensors still offer reasonable accuracy for many agricultural and environmental monitoring needs, enabling informed decisions regarding irrigation scheduling and related actions (Adla *et al.*, 2020).

Capacitance sensors are widely used for measuring soil moisture content in smart agriculture. These sensors operate on the principle that the dielectric constant of soil changes with moisture content, causing a change in the capacitance of the sensor. By measuring the capacitance, the moisture content of the soil can be determined. While resistance-based sensors measure the electrical resistance of the soil, which changes with moisture content. The resistance is typically measured using electrodes inserted into the soil, and the moisture content is determined based on the relationship between resistance and moisture.

In general, low-cost resistive sensors are generally less accurate than capacitive sensors in measurements over extended periods, and they are more susceptible to temperature changes and corrosion (Chowdhury et al., 2022). Based on these findings, low-capacitive sensors will be used for the prototype design.

3.3 Network technologies and protocols

In the world of IoT (Internet of Things), the choice of network and protocol is a critical decision that directly impacts the efficiency and effectiveness of any application. Factors such as bit rate, range, and power consumption play a pivotal role in determining which network and protocol are best suited for a particular use case.

This section explores in depth these critical considerations, and a case will ultimately be made for the application of Long Range and Long Range Wide Area Network in the context of smart agriculture.

In the comparative analysis of networks and protocols for IoT applications, it is important to consider the relationship between data rare, communication range, power consumption, and other factors that define the performance of various wireless technologies. To aid in this understanding, Figure 3.1 is presented.

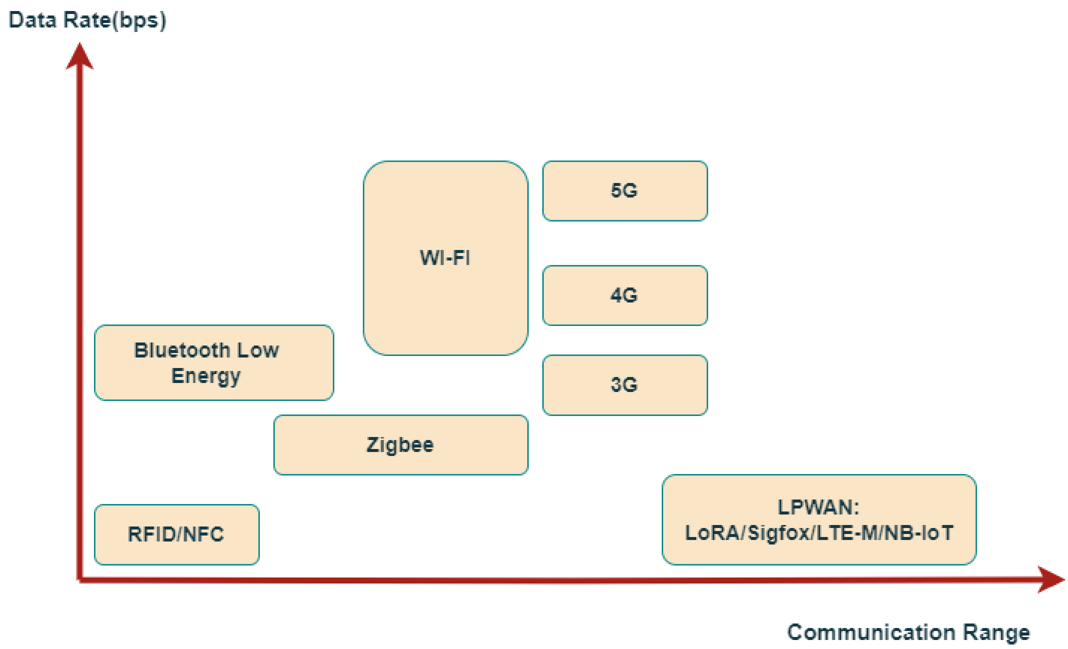

Figure 3.1: **Wireless Communication Technologies: Data Rate vs Communication Range**

This visual representation provides insights into how different wireless technologies perform in terms of data rate and communication range. These insights will facilitate informed decisions about the suitability of these technologies for specific IoT use cases.

3.3.1 Bit Rate

Bit rate, often referred to as data rate, measures the speed at which data can be transmitted over a network. It's a crucial factor in IoT applications as different use cases require varying degrees of data throughput. Higher bit rates allow for more data to be transmitted, but they also require more power.

- **Wi-Fi and Cellular Networks:**
  These networks offer high bit rates, making them ideal for applications that involve large data transfers or require real-time communication. However, they consume more power (Pagano et al., 2023) and may not be suitable for battery-powered IoT devices.

- **Bluetooth and Zigbee**:
  These networks offer moderate bit rates, making them suitable for applications that involve periodic data exchange or device-to-device communication. They strike a balance between data rate and power consumption.

- **LoRa and LoRaWAN**:
  LoRa networks provide low bit rates compared to Wi-Fi and cellular networks (Navarro, Costa and Pereira, 2020). While this might seem like a disadvantage, it is an advantage in many IoT scenarios where the focus is on conserving power and extending the range. LoRa's low bit rate is perfect for applications that involve sporadic data transmission, such as environmental monitoring in agriculture.

3.3.2 Range

Range refers to the maximum distance over which IoT devices can communicate with each other or with a network gateway. The range is a critical consideration in agriculture, where fields can span vast areas.

- **Wi-Fi and Cellular Networks**:
  These networks have a relatively limited range, especially in rural areas. Extending their range would require a dense infrastructure of access points or cell towers, making them less cost-effective for remote agriculture applications.

- **Bluetooth and Zigbee:**

  These networks offer a moderate range, typically suitable for indoor or short-range outdoor applications. However, they may struggle to cover larger agricultural fields effectively (Pagano et al., 2023).

- **LoRa and LoRaWAN:**

  LoRa devices are ideal for smart agriculture in rural areas, with their long-range capabilities that enable communication over several kilometres (Klaina et al., 2022). This makes them perfect for use with sensors that are scattered across large areas.

3.3.3 Power Consumption

Power consumption is the amount of power that the devices use to communicate, is a critical factor in IoT, especially for battery-powered devices deployed in remote locations.

- **Wi-Fi and Cellular Networks:**

  These networks are power-hungry, often requiring frequent data exchanges and a continuous connection to a power source (Dupont et al., 2018). This makes them less suitable for battery-operated sensors in remote agricultural settings.

- **Bluetooth and Zigbee:**

  These networks have moderate power requirements, making them viable for battery-powered devices. However, they may still need relatively frequent battery replacements or recharging.

- **LoRa and LoRaWAN:**

  LoRa's ultra-low power consumption is one of its standout features. LoRa devices can operate on a single battery for years, ensuring minimal maintenance and operational costs for smart agriculture applications (Dupont et al., 2018).

3.3.4 Conclusion: LoRa and LoRaWAN for Smart Agriculture

After a comprehensive analysis of networks and protocols in IoT, it is evident that LoRa and LoRaWAN are the ideal choices for smart agriculture applications. Their low bit rate, extended range, and ultra-low power consumption perfectly align with the requirements of agriculture in remote and expansive fields. LoRa technology allows agricultural sensors to communicate data reliably over long distances while consuming minimal power. LoRaWAN provides the necessary network infrastructure to connect these devices to the internet, ensuring that farmers can access real-time data on soil moisture, weather conditions, and crop health without the need for frequent battery replacements or extensive infrastructure investments. In the context of smart agriculture, LoRa and LoRaWAN enable cost-effective, efficient, and sustainable solutions that empower farmers to make data-driven decisions and optimise their crop yields while conserving valuable resources.

3.4 Microcontroller (MCU) Selection for LoRa and LoRaWAN

In 3.3.4, the decision was made to employ LoRa technology and LoRaWAN for the application. The selection of an appropriate microcontroller (MCU) is crucial for the successful implementation of LoRa and LoRaWAN applications. The MCU serves as the heart of the system, responsible for managing communication with the LoRa module, processing sensor data, and implementing LoRaWAN protocol stack. To ensure optimal performance and compatibility, the MCU must meet specific requirements outlined in (Semtech, 2017).

3.4.1 Essential MCU Requirements

According to (Semtech, 2017), the MCU should possess the following minimum specifications:

- **MCU RAM:**
  8 KB
- **MCU Flash:**
  128 KB
- **AES 128-bit cryptography:**
  Support for AES decryption in software.
- **Radio DIOs:**
  Connection of radio DIO pins to MCU IRQ inputs, specifically DIO0, DIO1, and DIO2
- **Communication Interface:**
  The MCU should support the necessary communication interfaces for connecting with the LoRa transceiver modules. Common interfaces include SPI (Serial Peripheral Interface) and I2C (Inter-Integrated Circuit).

3.4.2 Recommended MCU Specifications

While the minimum requirements ensure basic functionality, it is recommended to consider the following enhanced specifications for optimal performance and future scalability:

- **MCU RAM:**
  16 KB or higher
- **MCU Flash:**

256 KB or higher

- **Hardware Cryptographic Acceleration:**
  Dedicated hardware for AES encryption/decryption
- **Real-Time Clock (RTC) with Sub-Second Resolution:**
  Ability to maintain accurate timekeeping for LoRaWAN protocol synchronisation.
- **Secure Element:**
  Integration of a secure element for enhanced security and cryptographic operations

3.4.3 Additional Considerations

Beyond the technical specifications, it is essential to consider the following factors when selecting an MCU for LoRa and LoRaWAN applications:

- **Power Consumption:**
  LoRa and LoRaWAN applications often demand low power consumption to ensure extended battery life.
- **Peripheral Support:**
  The MCU should provide adequate peripheral interfaces for connecting sensors, actuators, and other external devices.
- **Development Environment and Tools**:
  A well-supported development environment with comprehensive tools and libraries can significantly simplify the development process.

3.4.4 Security Considerations

LoRaWAN applications often involve the transmission of sensitive data, making security a paramount concern. The MCU should support AES 128-bit encryption to safeguard sensitive data exchanged over the LoRaWAN network. Additionally, the use of a secure element, such as a hardware cryptographic module, is recommended to further enhance security.

3.4.5 Power Consumption

In the context of this thesis, where battery life is a critical factor, it is advisable to consider low-power MCU options to complement the energy-efficient nature of LoRa technology.

3.4.6 Conclusion

The selection of an appropriate MCU is a critical step in the development of LoRa and LoRaWAN applications. By thoughtfully considering both the minimum and recommended requirements, in addition to factors such as power consumption, peripheral support, and available development tools, the successful implementation of LoRaWAN solutions can be guaranteed.

3.5 Technical Insights into LoRa and LoRaWAN

In 3.3, a comparative analysis of networks and protocols suitable for IoT applications was conducted, wherein LoRa and LoRaWAN emerged as compelling candidates. Their unique attributes, including low bit rate, extended range, and remarkable power efficiency, have captured the IoT community's attention, particularly in addressing the challenges posed by agricultural operations across expansive, often remote terrains. This subheading delves deep into the technical intricacies of LoRa and LoRaWAN, where modulation schemes, transmission times, bit rates, coding rates, and spreading factors are thoroughly explored. This comprehensive analysis gives a complete understanding of how LoRa enables efficient wireless communication.

In addition to the exploration of technical intricacies, a comprehensive classification of LoRaWAN into three categories: Class A, Class B, and Class C, is also conducted. Each classification offers distinct operational modes tailored to meet specific IoT requirements. Class A was chosen for this project as it aligns with the requirements.

3.5.1 LoRa

3.5.1.1 LoRa Modulation

LoRa modulation is a wireless communication technology specifically developed for low-power, wide-area networks (LPWANs) that operates within the ISM (Industrial, Scientific, and Medical) bands. It offers the ability to establish long-range connections while maintaining low data rates, making it an ideal choice for applications that require low power consumption, extended battery life, and connectivity across vast distances. The technology employs a proprietary spread spectrum modulation scheme that is derived from Chirp (Compressed High-Intensity Radar Pulse) Spread Spectrum (CSS) modulation (Semtech, 2015), which utilises a continuously ascending or descending frequency signal for data encoding. This unique approach ensures exceptional resilience to noise and interference, enabling reliable data transmission over long distances, even in challenging environmental conditions.

3.5.1.2 Spreading Factor

In LoRa, the duration of each symbol (Ts) is determined by the Spreading Factor (SF), which represents the number of chips per symbol and defines the rate at which chirp waveforms are transmitted. As the SF increases, the duration of the symbol transmission also increases. This relationship is illustrated in Equation 3.1

$$Ts = \frac{2^{SF}}{BW} \text{ secs} \tag{3.1}$$

Where:

- **Ts** is the symbol period,
- **BW** is the bandwidth of the modulation signal.
- **SF** is the spreading factor.

In a given bandwidth, the duration of symbol transmission in SF(n) is double that of SF(n-1), where n represents the number of bits transmitted in a symbol. This relationship is depicted in Table 3.1, where Equation 3.1 and Equation 3.2 are used to populate Table 3.1. The two equations show that the symbol transmission time increases as the spreading factor increases.

$$Ts(_{SFn}) = 2 * Ts(_{SF(n-1)}) \tag{3.2}$$

Table 3.1: **Transmission Time Symbols for BW125**

Spreading Factor	Ts
SF7	1.024 ms
SF8	2.048 ms
SF9	4.096 ms
SF10	8.192 ms
SF11	16.384 ms
SF12	32.768 ms

Furthermore, the spreading factor plays a vital role in LoRa's spread spectrum modulation. It influences the symbol rate (Rs), which is the rate at which the spread of information is transmitted, and it is the reciprocal of Ts (Semtech, 2021). It is calculated using the formula:

$$Rs = \frac{BW}{2^{SF}} \text{ symbols/sec} \tag{3.3}$$

Where:

- **Rs** is the symbol rate in bits per second.

- **BW** is the bandwidth of the modulation signal.
- **SF** is the spreading factor.

By selecting a higher spreading factor, the receiver sensitivity improves, as Table 3.2 shows (STMicroelectronics, 2023), resulting in an increased link budget and longer range. However, this improvement comes at the expense of a longer transmission time.

Table 3.2: **Lora Spreading Factor, Chips/Symbol, and Sensitivity**

SF	5	6	7	8	9	10	11	12
2^{SF} (Chips/Symbol)	32	64	128	256	512	1024	2048	4096
LoRa Demodulator SNR (dB)	-2.5	-5	-7	-9.5	-12	-14.5	-17	-19

3.5.1.3 Bit Rate

In a LoRa communication system, the bit rate refers to the rate at which binary data is transmitted through the radio link. This rate is subject to variation and is dependent on the selected spreading factor (SF) and bandwidth (BW) settings. To calculate the bit rate, the formula below is used:

$$Rb = SF * \frac{BW}{2^{SF}} \text{ bps} \quad (3.4)$$

LoRa communication systems are made more reliable by cyclic error coding for forward error detection and correction. Forward Error Correction (FEC) is effective at improving link reliability in the presence of interference. As detailed in Table 3.3, various coding rates are associated with specific cyclic coding rates and overhead ratios, offering a range of options to optimise the system's performance. The coding rate and interference robustness can be dynamically adjusted to match channel conditions. The selected coding rate is communicated from the transmitter to the receiver in the header. If it is included. A higher coding rate provides better noise immunity but at the cost of longer transmission times. In normal conditions, a coding rate of 4/5 is a good balance between noise immunity and transmission time. A higher coding rate can be used in the presence of strong interference. The error correction code is encoded in the packet header, so the receiver does not need to know it in advance. This means that the modems can dynamically adjust the coding rate without having to re-configure the receiver (Semtech, 2021). Therefore, the nominal bit rate of the data signal can be defined as (Semtech, 2015):

$$Rb = \left(SF * \frac{BW}{2^{SF}}\right) * \left(\frac{4}{4+CR}\right) \text{ bps} \quad (3.5)$$

Where:

- **CR** is the coding rate and varies from 1 to 4.
- **BW** is the bandwidth of the modulation signal.
- **SF** is the spreading factor.

Table 3.3: **Coding Rate and Overhead Ratio**

Coding Rate	Cyclic Coding Rate (Raw bits/ total bits)	Overhead Ratio
1	4/5	1.25
2	4/6	1.5
3	4/7	1.75
4	4/8	2

3.5.1.4 LoRa Bandwidth

Increasing the signal bandwidth in a LoRa system allows for faster data transmission but comes at the cost of reduced sensitivity, a smaller link budget, and a shorter communication range (STMicroelectronics, 2023). This trade-off needs to be carefully considered when designing or configuring a LoRa communication system, as it can impact the system's performance in different scenarios.

Table 3.4: **LoRa System Performance Metrics** (Semtech, 2019c)

Bandwidth (KHz)	Spreading Factor	Coding Rate	Nominal Rb (bps)	Sensitivity (dBm)
125	12	4/5	293	-136
250	12	4/5	586	-133
500	12	4/5	1172	-130

To check for consistency of Table 3.4, Equation 3.5 is employed, and the results match.

$$Rb = 12 * \left(\frac{125000}{2^{12}}\right) * \left(\frac{4}{5}\right) = 292,968 \ = 293 \ bps$$

$$Rb = 12 * \left(\frac{250000}{2^{12}}\right) * \left(\frac{4}{5}\right) = 585,937 \ = 586 \ bps$$

$$Rb = 12 * \left(\frac{500000}{2^{12}}\right) * \left(\frac{4}{5}\right) = 1171,875 = 1172 \ bps$$

3.5.1.5 LoRa Frame

A LoRa frame is a data packet that is transmitted using the LoRa physical layer protocol. It can be either explicit or implicit. The explicit frame, which is the default mode, includes a header that contains information about the payload size, coding rate, and optional 16-bit CRC (Cyclic Redundancy Check). This allows the receiver to identify and dispose of any headers that do not meet the validity criteria. On the other hand, the Implicit frame does not include a header and requires prior knowledge of the payload size and coding rate (Semtech, 2021).

Figure 3.2 illustrates the structure of the LoRa frame, which is as follows:

- **Preamble:**

  The preamble is used to synchronize the receiver with the transmitter. By default, it consists of 12 symbols long and can be adjusted as needed.

- **Header (optional):**

  The header contains information about the payload size, coding rate, and whether CRC is used.

- **Payload:**

  The payload contains the actual data that is being transmitted.

  CRC:

- The CRC is utilised to identify transmission errors.

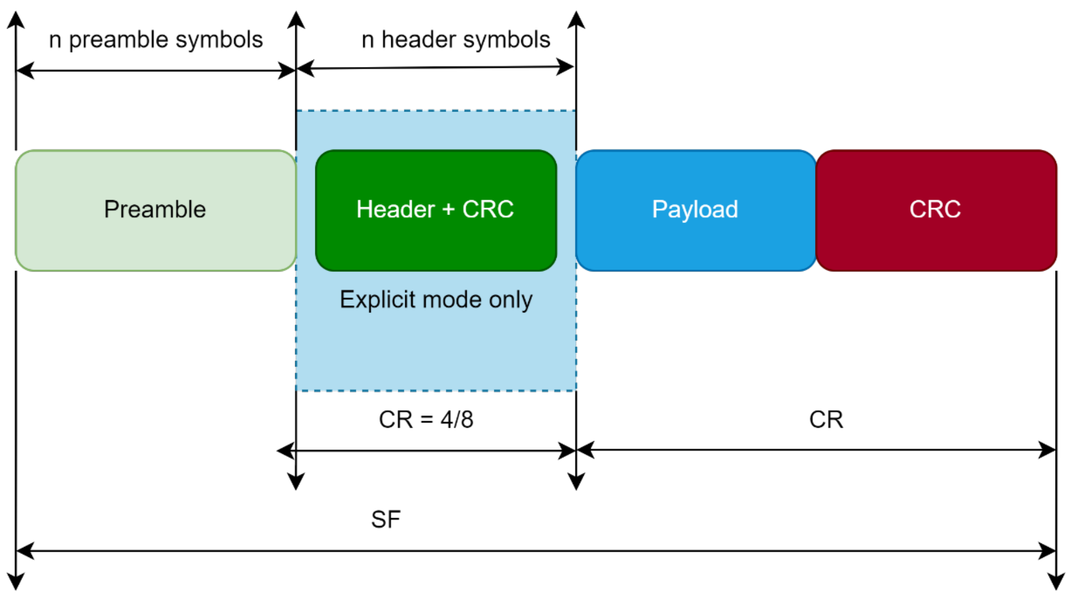

Figure 3.2: LoRa Frames Format

3.5.1.6 Time on Air

LoRa time on air (ToA) is the amount of time it takes for a LoRa packet to be transmitted from the end device (source) to the gateway (destination). The ToA depends on several factors, including the SF, CR, and BW.

The formula for calculating the ToA is as follows:

$$ToA = Nsymbol * Ts \ \ (ms) \tag{3.6}$$

$Nsymbol$ represents the number of symbols contained within the LoRa frame and the formula is provided as follows (Semtech, 2021):

$$Nsymbol = (n_p + 4.25 + 8 + ceil\left(\frac{\max(8*PL+CRC-4*SF+8+H,0)}{4*(SF-(2*LDR))}\right) * (CR + 4) \tag{3.7}$$

Where:

- **PL** refers to the size of the user data payload.
- **SF** represents the Spreading Factor 7 to 12.
- **H** is set to 20 with an explicit header and 0 with an implicit header
- **LDR** is set to 1 if low data rate optimisation is activated and to 0 when it is not.
- **CR** denotes the coding rate, which ranges from 1 to 4.
- **CRC** equals 16 when CRC is enabled and 0 when it's not.

The real bit rate can now be calculated using the following equation (STMicroelectronics, 2023), where:

$$RealBitRate = \frac{PL*8}{ToA} \ (bps) \tag{3.8}$$

3.5.2 LoRaWAN

LoRaWAN is an open, low-power, long-range wireless communication protocol designed for IoT that enables devices to securely connect to the Internet, exchange data over long distances with minimal power consumption, and offers mobility and localisation services, all standardised by the LoRa Alliance (Semtech, 2019b). The LoRa Alliance® is a non-profit organisation founded in 2015 to drive the development and advancement of LoRaWAN technology and its ecosystem. It comprises global companies, universities, and other organisations heavily invested in promoting the growth of LoRaWAN as a leading IoT connectivity solution (Alliance, n.d).

The LoRa Alliance plays a pivotal role in maintaining and enhancing the LoRaWAN technology standard, ensuring its security, scalability, and global compatibility. By supporting the expansion of LoRaWAN networks worldwide, the Alliance facilitates a wide range of IoT use cases and applications, leveraging the technology's long-range capabilities and energy efficiency.

3.5.2.1 Components of a LoRaWAN Network

As shown in Figure 3.3, the LoRaWAN network employs a star-of-stars topology (LoRa Alliance, 2020) that consists of several essential components:

- **End Nodes:**

  These are the IoT devices or sensors that collect and transmit data. They serve as the originating point of data within the network and use LoRa technology to communicate with one or multiple gateways.

- **Gateways:**

  Acting as intermediaries, gateways are also referred to as concentrators or base stations that facilitate two-way communication between end nodes and the already configured network server. They play a critical role in connecting the wireless LoRaWAN protocol used by End Nodes with standard IP connections.

- **Network Server:**

  Serving as the central coordinator of the LoRaWAN network, the Network Server enforces the LoRaWAN protocol, verifies the authenticity and reliability of End Nodes using a 128-bit Advanced Encryption Standard (AES) key known as NwkSKey (Network Session Key), eliminates duplicate uplink messages that might occur as a result of multiple Gateways relaying the same message to the Network Server, chooses the gateways for transmitting downlink data, and issues ADR (Adaptive Data Rate) commands to enhance the data rate efficiency of the End Nodes (Semtech, 2019b). In cases where the authentication process is unsuccessful, the Network Server discards the LoRaWAN message. Conversely, if the authentication process is successful, the Network Server forwards the message to the Application Server.

- **Application Servers:**

  The Application Server has two main functions. Firstly, it decrypts the data received from the sensors. Secondly, it encrypts the data that is meant for End Nodes using a 128-bit AES key called AppSKey (Application Session Key). This processed data is then integrated into pre-existing data management systems or IoT. Additionally, the Application Server interprets sensor application data and produces application-layer downlink payloads that are delivered to connected End Nodes (Semtech, 2019b).

- **User Application Section:**

  The User Application section, although not directly part of the LoRaWAN network, is where the processed data generated by IoT devices becomes accessible to end-users. This section usually includes mobile phones and laptops, which enable users to access and interact with the data.

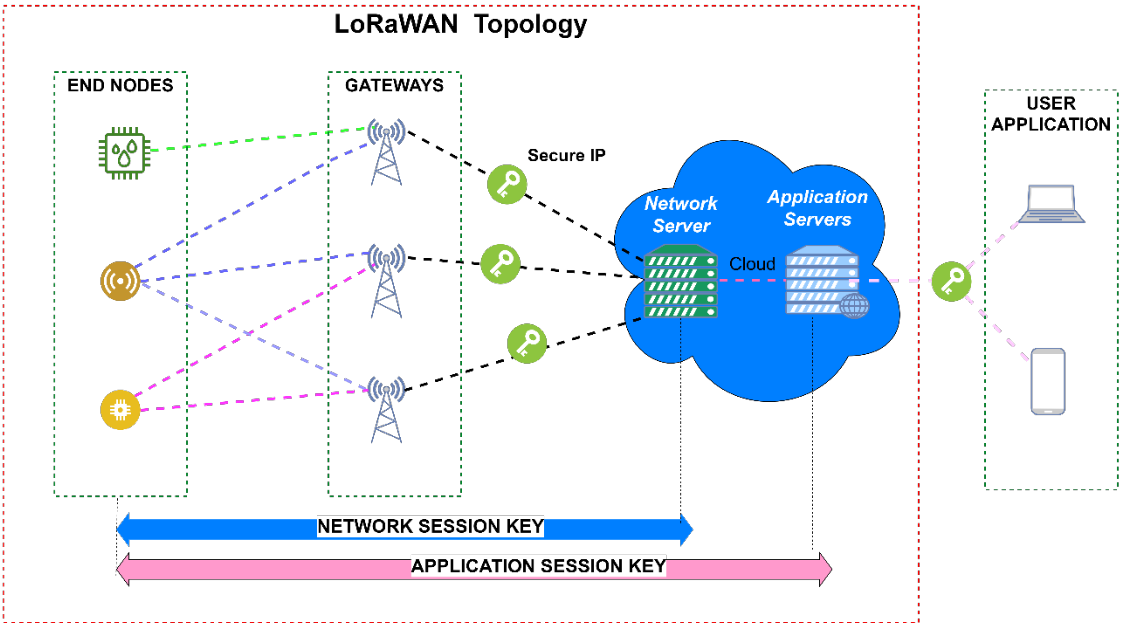

Figure 3.3: LoRaWAN Topology

3.5.2.2 LoRaWAN End Node Classes

In a LoRaWAN network, End Nodes are classified into three different classes as illustrated in Figure 3.4, namely Class A, Class B, and Class C. Each class defines the operating characteristics of the End Nodes and the way they communicate with the network, as well as the power-saving mechanisms used. These classes have distinct features and communication patterns that make them suitable for different applications.

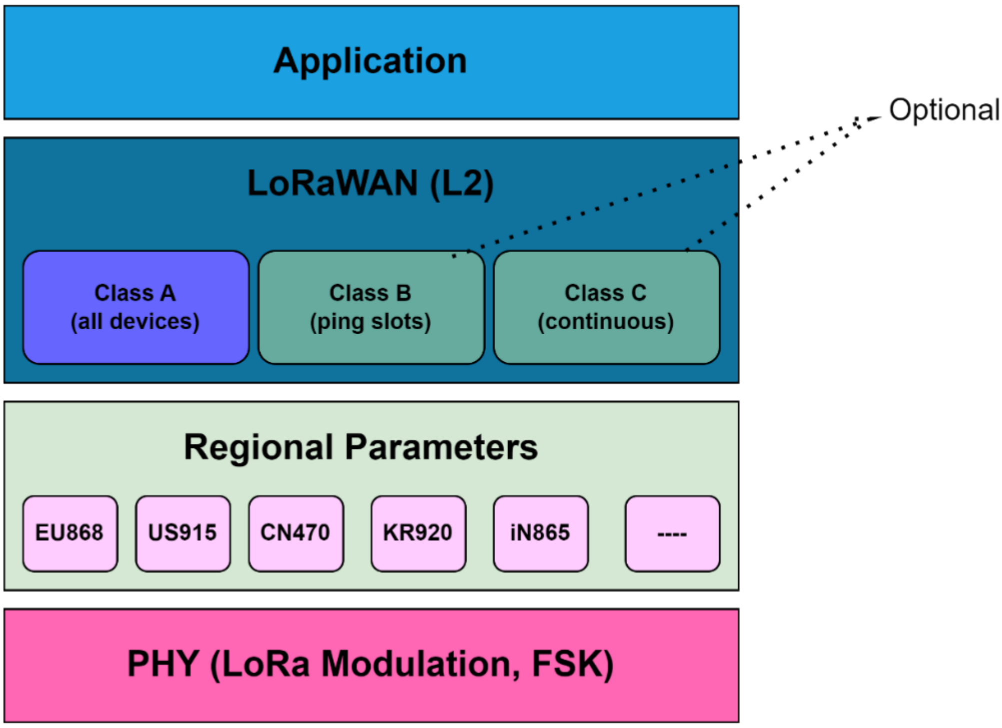

Figure 3.4: LoRaWAN Classes

3.5.2.3 Class A

Class A, which is supported by all End Nodes is characterised by a communication pattern where the End Node initiates communication. Any downlink messages from the Network Server are held in a queue until the next uplink message is received from the End Node, at this point, a receive window is opened. This design is particularly suited for applications that rely on receiving downlink data in response to an uplink transmission or can accommodate downlink scheduling with flexible latency requirements (Semtech, 2019a).

After an uplink transmission, a Class A End Node initiates a short receive window called Rx1. If no downlink data is received during this period, it proceeds to open a second received window called Rx2 as illustrated in Figure 3.5. When a preamble is identified within a receive window, the radio receiver remains operational until the entire downlink frame is successfully demodulated. If, during the first receive window, a frame is detected, demodulated, and passes address and MIC (Message Integrity Check) checks, and it is intended for the specific end device, the second receive window remains closed (Alliance, 2018). The starting time for Rx1 commences after a fixed duration following the conclusion of the uplink transmission. By default, the delay, referred to as RECEIVE_DELAY1, is set to 1 second. Rx2 generally commences 2 seconds after the uplink transmission concludes. The specific timing relationship between the uplink, RECEIVE_DELAY1, and RECEIVE_DELAY2 is region-specific and detailed in (Alliance, 2021).

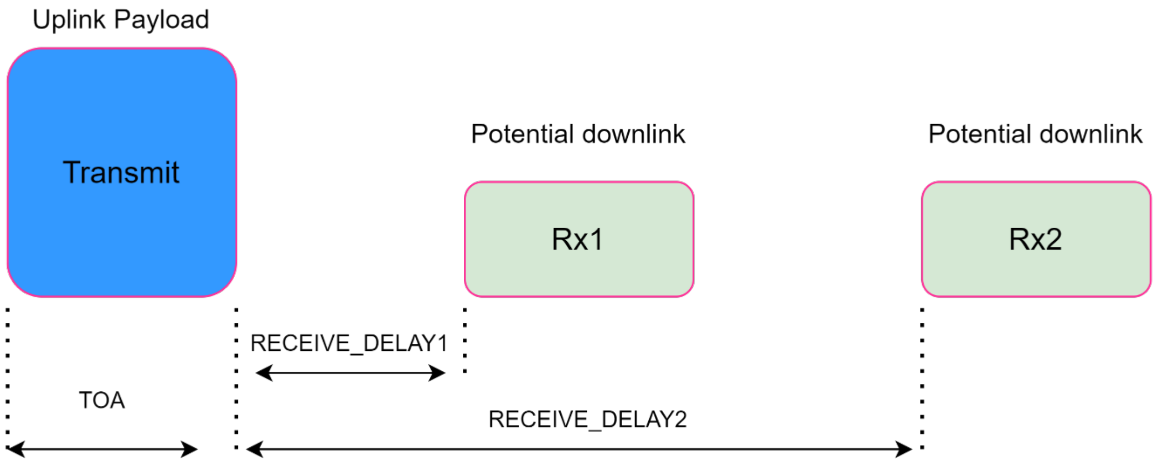

Figure 3.5: Class A Communication Pattern

3.5.2.4 Class B

LoRaWAN Class A has a limitation in its Aloha data transmission method, as it lacks a predictable response time when there is a need for communication between the customer application or server and the end node. To address this, Class B provides a solution by ensuring that an End-Node is available for reception at a scheduled time. This is achieved by extending the receive windows beyond Class A's default two windows. Class B devices periodically open additional receive windows as specified by a time-synchronised schedule, allowing for more frequent downlink data reception from the network. However, this extended operation consumes more power than Class A. The gateway facilitates synchronisation by periodically sending a beacon to align all end devices in the network. This synchronisation enables the end device to open a brief additional reception window, known as a 'ping slot,' at a predetermined time within a regular time slot (Alliance, 2018), as illustrated in Figure 3.6.

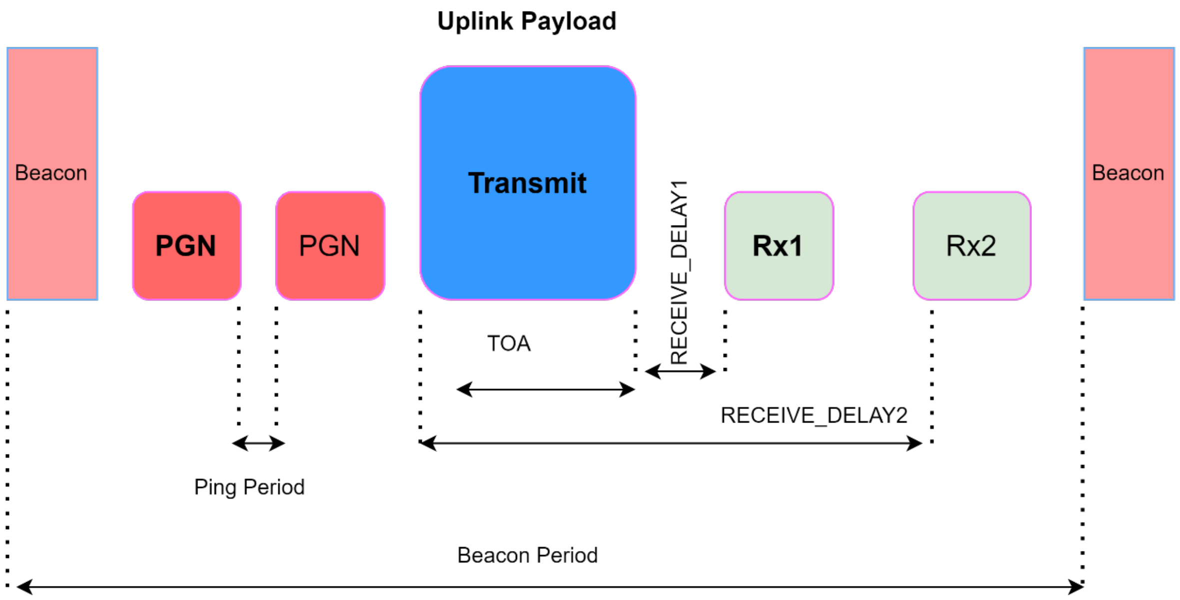

Figure 3.6: Class B Communication Pattern

3.5.2.5 Class C

Class C devices, unlike Class A and Class B, keep their receive windows open all the time except when transmitting. They achieve this by opening a short Rx2 window after each uplink transmission and closing it when the Rx1 receive window begins. They then switch to Rx2 mode and keep it open until they need to send another uplink message, as illustrated in Figure 3.7. This means they can receive data from the network at any given moment, making them suitable for applications that require continuous communication. However, it's important to note that this continuous operation comes at the expense of higher power consumption. As a result, Class C devices are typically designed for mains-powered operation (Alliance, 2018).

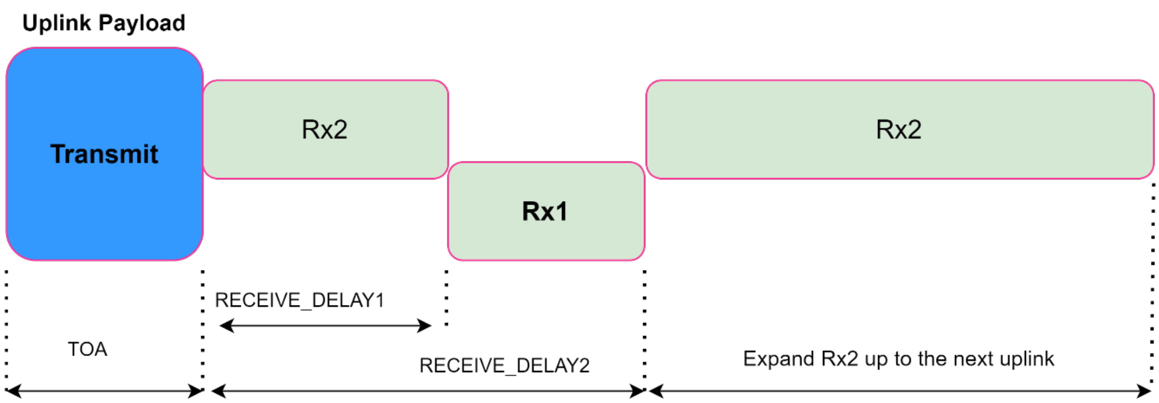

Figure 3.7: Class C Communication Pattern

3.5.2.6 LoRaWAN End Device Activation Methods

To join a LoRaWAN network, all End Nodes need to be activated. There are two activation methods: over-the-air activation (OTAA) and activation by personalisation (ABP). Both methods establish confidential session keys, which are stored by both the end device and the network server. These keys play a crucial role in securing the transmission and reception of messages across the network. In ABP, the session keys are loaded onto the end device during the manufacturing process, while in OTAA, they are generated dynamically through a series of interactions with the network server, known as the join procedure, which requires that the End-Node be preconfigured with the following details before starting the process: a DevEUI (a globally unique identifier for the end-device), an AppEUI (the application identifier), and an AES-128 key knows as AppKey (Alliance, 2018).

The successful implementation of either mode relies on managing three vital parameters: DevAddr for device identification, NwkSKey for authentication, and AppSKey for encryption. This ensures that every access to the genuine and secure network is exclusively granted to authorised devices. OTAA is the preferred choice for enhanced security (Semtech, 2019b), allowing key replacement and configuration optimisation during the join process.

3.5.2.7 LoRaWAN Frames

The LoRaWAN MAC message format is a standardised way of encapsulating data that is transmitted between LoRaWAN devices. As Figure 3.8 shows, the format consists of three parts:

1. **MAC Header (MHDR):**
   The MHDR is a one-byte field that identifies the type of MAC message. There are eight different types of MAC messages, including join requests, join accepts, and data messages.

2. **MAC Payload:**
   The MAC payload is a variable-length field that carries the actual data being transmitted. The MAC payload can contain either application data or MAC commands.

3. **Message Integrity Code (MIC):**
   The MIC is a four-byte field that is used to verify the integrity of the MAC message. The MIC is calculated across all the message fields using a cryptographic algorithm, and it is appended to the end of the MAC payload before the message is transmitted.

The LoRaWAN MAC message is designed to be efficient and reliable. It uses a minimum number of bytes to transmit the necessary information, and the MIC ensures that the message has not been tampered with.

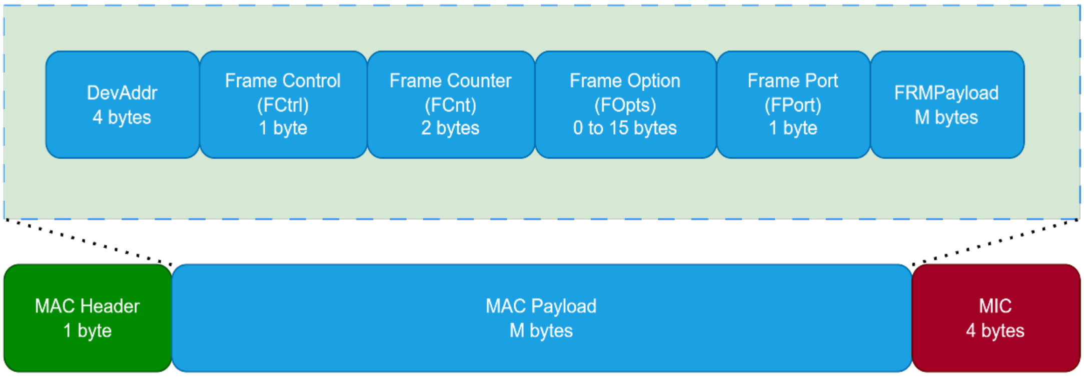

Figure 3.8: LoRa Payload with LoRaWAN Elements

3.5.3 Conclusion

In conclusion, after a comprehensive exploration of LoRa and LoRaWAN technologies, this study opts for the utilisation of Class A for its significant battery efficiency. Additionally, OTAA is chosen over ABP due to its enhanced security features. These strategic choices aim to optimise the performance and security of the LoRaWAN network in the context of this study.

Regarding LoRa, it supports spreading factors ranging from 7 to 12, each corresponding to a specific symbol duration. Higher spreading factors provide greater robustness against interference and improved sensitivity, making them suitable for long-range and low-power applications (Semtech, 2015). However, this comes at the expense of lower data transmission rates due to the longer symbol duration.

Overall, the choice of spreading factor in LoRa is a trade-off between data rate, range, and power consumption, with higher spreading factors offering longer range but lower data rates.

3.6 Summary

In this chapter, the theoretical foundations necessary for the development of an integrated IoT and cloud computing platform tailored for smart agriculture have been covered. The discussion began with an in-depth examination of key concepts such as sensors, processors, data storage, and network technologies and protocols. The integration principles were delved into, highlighting how these components can be selected to work together to form a cohesive system. Additionally, the roles of LoRa and LoRaWAN in facilitating long-range, low-power communication within the smart agriculture framework were explored. It was demonstrated how these technologies contribute to the efficient transmission of data from distributed sensors to the central cloud platform. By understanding these fundamental elements, the theoretical basis for the platform and its potential to significantly reduce water loss, enhance crop development, and boost productivity for farmers across different income levels were illustrated. The comprehensive coverage of these topics establishes a solid foundation for the subsequent practical implementation and analysis of the integrated IoT and cloud computing platform in smart agriculture.

CHAPTER FOUR
SYSTEM DEVELOPMENT AND IMPLEMENTATION

4.1 Introduction

Smart agriculture represents a technology-driven paradigm that leverages advanced sensors, data analytics, and automation to revolutionise farming practices. This approach aims to enhance crop yields, optimise resource utilisation, and promote environmental sustainability. The integration of technology into agriculture offers farmers substantial benefits, ranging from increased productivity and cost reduction to improved environmental outcomes.

This research aims to contribute to the advancement of smart agriculture by developing and implementing a system utilising IoT and Cloud Computing. The system consists of a network of sensors, a robust data management platform, and an intelligent decision-support system. These sensors capture real-time data on various environmental parameters, such as soil moisture and temperature. The operational IoT platform, now in full function, consistently captures and analyses this data, with a focus on achieving objectives such as water loss prevention, optimising crop growth, and maximising production.

The methodology for this study adopts a quantitative approach, emphasising the development and assessment of crop monitoring and irrigation systems using IoT and Cloud Computing. This approach involves the real-time quantitative analysis of data actively captured by the operational IoT platform to achieve water loss prevention, optimising crop growth, and maximising production.

4.2 System Design

The study was strategically structured into two main phases to ensure a comprehensive and effective development process. This approach facilitated a methodical progression from the conceptualisation and creation of the IoT platform to its practical implementation and validation in a real-world agricultural setting.

During the initial phase, the focus was on conceptualising and developing the IoT platform. This included designing the system architecture, selecting hardware components, and integrating IoT and cloud computing technologies. The goal was to create a scalable and efficient platform capable of gathering, processing, and analysing real-time agricultural data.

The second phase centred on the implementation of the developed IoT platform. This phase involved configuring the hardware components, establishing communication protocols, and deploying the system in the field. The primary goal was to ensure the operational functionality of the system and validate its effectiveness through extensive testing and user interaction. Key activities included system configuration, field deployment, and rigorous testing to verify the system's reliability and accuracy, along with the introduction of enhanced features like edge-level decision-making capabilities for autonomous irrigation control.

4.2.1 Phase 1: Development of IoT Platform

4.2.1.1 System Architecture

The IoT platform was designed with a multi-tiered architecture that includes edge devices, a communication layer, a data processing layer, and a cloud-based storage and analytics layer. The platform's performance and scalability were optimised by considering quantitative factors such as data transmission rates, range, and storage capacities. Figure 4.1 illustrates a visual representation of the architectural framework employed in system development.

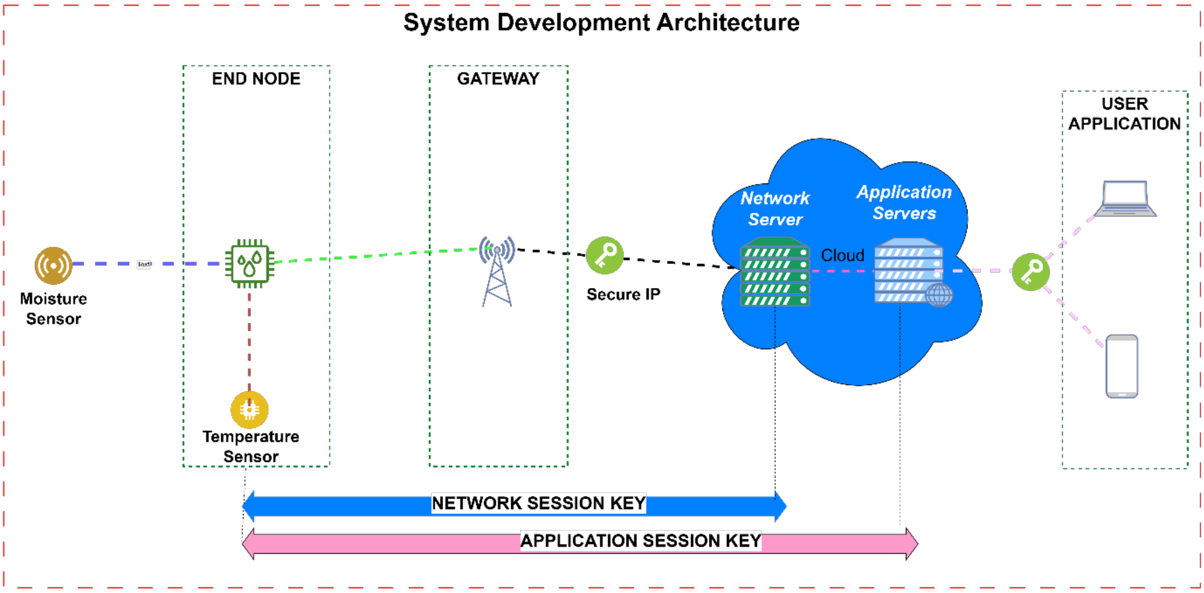

Figure 4.1: **Sensor-to-Cloud Framework for Agriculture Data Processing and Monitoring**

This architecture enabled the platform to support an autonomous irrigation control system that relies on data insights and algorithms. Moreover, the platform features a user interface (UI) that is accessible through laptops and mobile devices, allowing users to view real-time data. If users desire, they can also use the same interface to initiate irrigation actions, creating a dual control mechanism for irrigation processes. This dual control feature, considering the range of user-initiated actions, enhances user engagement, enabling farmers to passively rely on the automated irrigation system or actively initiate irrigation based on their preferences. The detailed functionality and impact of this dual control system were explored further in Chapter 5.

4.2.1.2 System Components

After exploring the architectural design that underlies the IoT platform, this section examines the individual components driving the system's operations. The implementation of the prototype design in this study involved the careful selection of several hardware components. This selection process was crucial to ensuring the successful development and evaluation of the proposed IoT-based soil moisture monitoring system.

4.2.1.2.1 Soil Moisture Sensor

As outlined in section 3.2, the decision was made to employ low-capacitive soil moisture sensors within the IoT platform. These sensors are critical components designed to provide precise and efficient data on soil conditions, aligning with the main goals of water conservation and optimised irrigation practices. The selection of low-capacitive sensors was driven by their capability to offer accurate measurements while minimising power consumption.

For this study, a low-cost capacitive soil moisture sensor SKU:SEN0308, manufactured by DFRobot, was selected for the prototype design. This sensor, recently introduced by DFRobot, features advancements such as increased waterproof performance, optimised corrosion resistance, an extended plate length, and improved circuit performance (DFRobot, no date). It offers an affordable and accessible solution for soil moisture measurement in smart agriculture applications. The sensor's wide input voltage range of 3.3V-5.5V and output voltage range of 0~2.9VDC (DFRobot, no date) enable its compatibility with various systems and ensure flexibility within the proposed IoT-based soil moisture monitoring system. Its specifications and performance characteristics, including the output voltage range, align with the requirements of this study, making it a suitable choice for integration into the prototype design. Figure 4.2 provides a visual representation of the selected sensor.

Figure 4.2: Soil Moisture Sensor

4.2.1.2.1.1 Calibration Procedure

Calibration procedure is used to ensure precise soil moisture measurements, the low-cost capacitive soil moisture sensor SKU:SEN0308 from DFRobot underwent a calibration process. The calibration involved the following steps, as recommended by DFRobot (DFRobot, no date):

i. Calibration Range

- Initiated by activating the serial port monitor and configuring the baud rate to 115200.
- Measured the sensor output when the probe was in open air, as illustrated in Figure 4.3, and recorded it as Reading 1. This reading signified the threshold for dry soil, indicating 0%RH humidity and fell within the range of 3593-3609 due to fluctuations in air humidity, as illustrated in Figure 4.4.

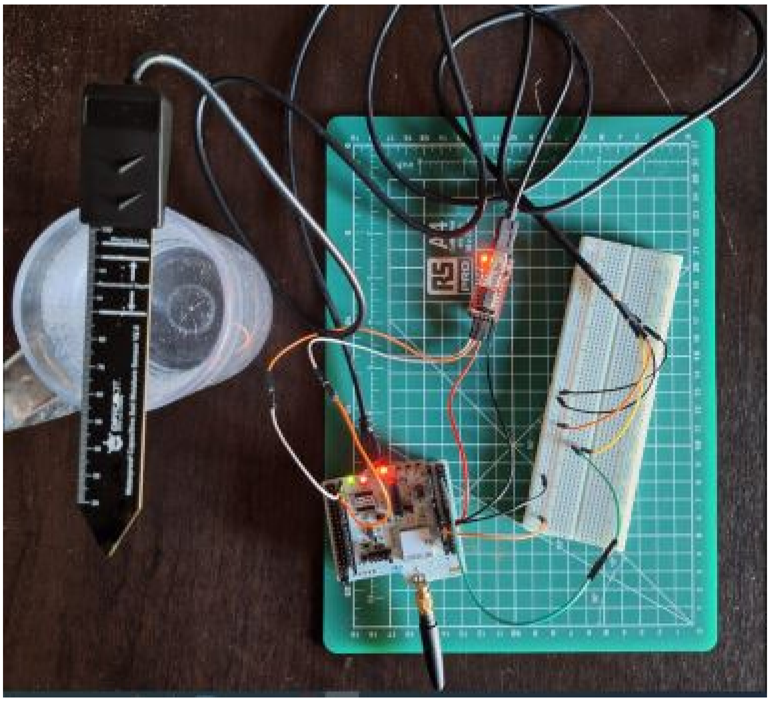

Figure 4.3: Dry Measurement

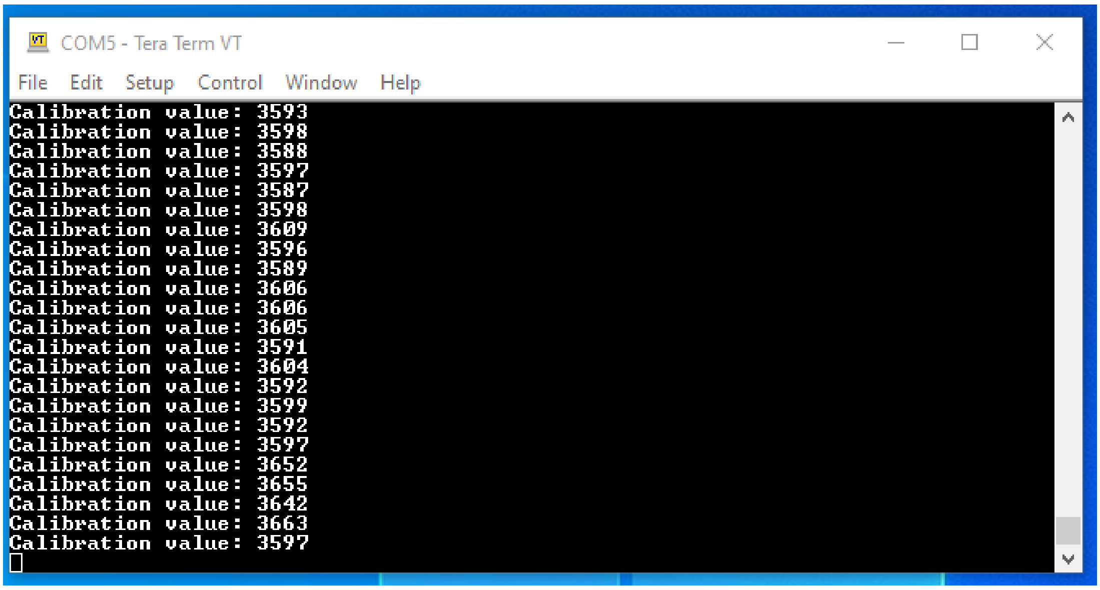

Figure 4.4: Sensor Dry Calibration

- Submerged the probe into a container of water, as illustrated in Figure 4.5 ensuring it reached a depth within the parameters of the 'Recommended Depth' and 'Warning Line' as indicated on the sensor board.
- Noted the sensor reading when it fluctuated between 392-401 in water and referred to the board's scale to record the insertion depth, as illustrated in Figure 4.6. This depth represented the threshold for moist soil at 100%RH humidity, and it was advised to maintain this depth during soil usage.

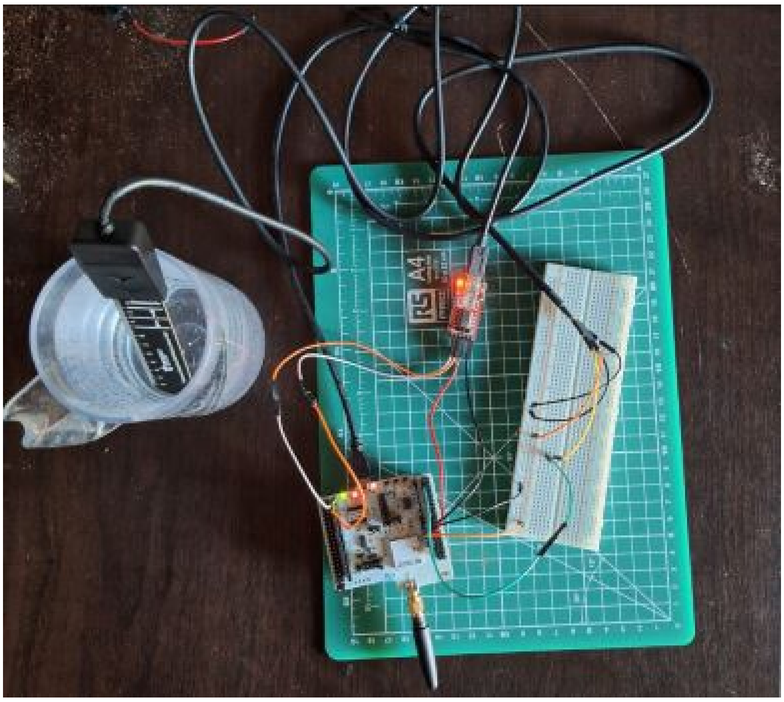

Figure 4.5: Water Measurement

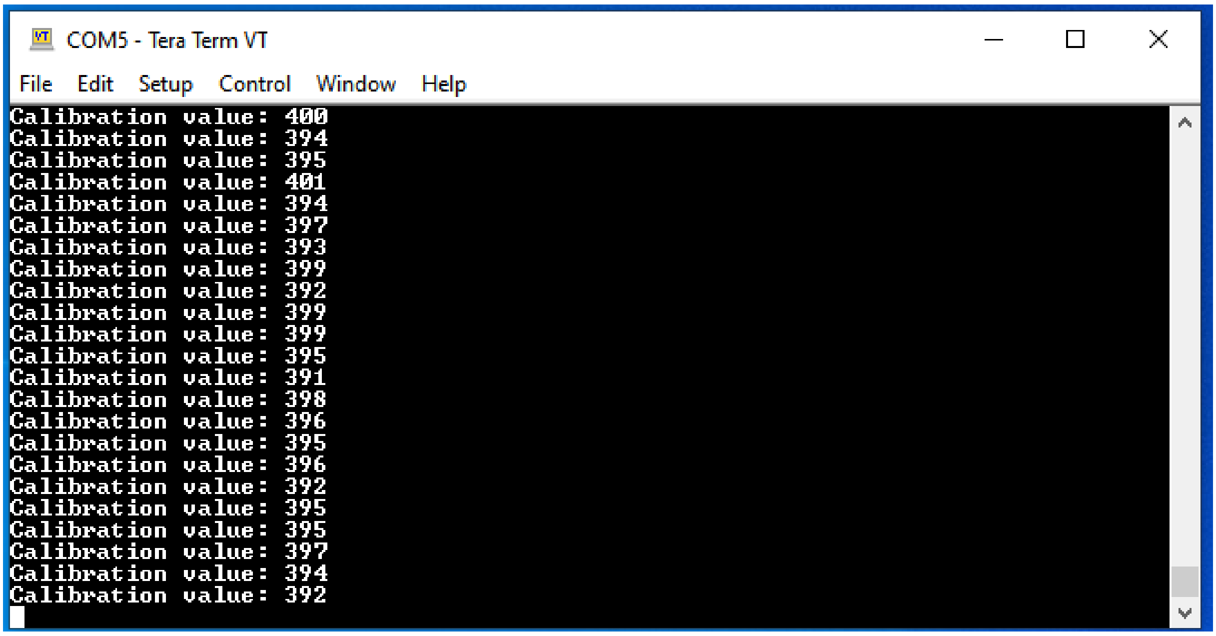

Figure 4.6: Sensor Water Calibration

ii. Section Settings

- The calibration range was divided into three sections: dry, wet, and very wet.
- The recorded values from the previous steps are used by the application software to determine the boundaries of these three sections: Dry, Wet, and Very Wet.

4.2.1.2.2 End Node

One of the central components chosen for its wireless capabilities and microcontroller functionalities is the NUCLEO-WL55JC2 development board from STMicroelectronics, as illustrated in Figure 4.7.

Figure 4.7: **NUCLEO-WL55JC2**

The NUCLEO-WL55JC2 features the STM32WL55JC System-On-Chip, which integrates Arm Cortex-M4 and Cortex-M0+ cores and a Sub-GHz radio that supports various wireless protocols, including LoRa, (G)MSK, G/FSK, and BPSK (ST, 2021:2). Its wireless capabilities make it an ideal choice for the wireless communication aspect of the soil moisture monitoring system, facilitating data transmission from the soil moisture sensors to the central monitoring unit. Its compatibility with popular integrated development environments, such as STM32CubeIDE, Keil MDK, and IAR Embedded Workbench, streamlines the development process and enables efficient firmware development and debugging.

The NUCLEO-WL55JC2 plays a crucial role as the central processing unit in the prototype design, managing tasks such as data acquisition, wireless communication, and sensor interfacing. Its versatility and support for various wireless protocols made it a suitable and robust choice for the envisioned crop monitoring and irrigation system application. Its energy-efficient operation ensures minimal power consumption, which is crucial for prolonged and uninterrupted operation in a remote agricultural setting.

Moreover, the NUCLEO-WL55JC2's compatibility with the STM32Cube development platforms, along with the availability of a comprehensive set of software libraries and examples, not only streamlined the development process but also accelerated the implementation of the prototype design. This compatibility facilitated firmware development, simplified LoRa and LoRaWAN stack implementation, and enhanced data management capabilities.

As stated in (Alliance, 2021), LoRa is bound to follow region-specific regulations and must operate on designated frequency channels defined by local authorities. In South Africa, LoRa operates on frequency channels mentioned in Table 4.1.

Table 4.1: Channel Plan per ISO 3166-1 Country (Alliance, 2021:18)

ISO 3166-1 Country name (Code alpha 2)	Band/channels	Channel Plan
South Africa (ZA)	433.05 - 434.79 MHz	EU433
	865 – 868.6 MHz	EU863-870
	868.7 – 869.2 MHz	EU863-870
	869.4 – 869.65 MHz	EU863-870
	869.7 – 870 MHz	EU863-870

The selected frequency band for this research is EU433, covering the spectrum of 433.05-434.79 MHz This decision ensures that the study aligns with local authorities and complies with established regional standards as required by the regulations.

Building upon these regulatory considerations, the study strategically implemented Class A for its commendable battery efficiency in end nodes. Similarly, the OTAA method is employed over ABP for enhanced security features. These decisions are crucial components of the methodology adopted in optimising the performance and security of the LoRaWAN network within the specific context of this research.

It's important to note that LoRa's support for spreading factors ranging from 7 to 12 has been considered, each corresponding to a specific symbol duration. The trade-off between data rate, range, and power consumption is a key factor, with higher spreading factors offering a longer range but lower data rate, as extensively discussed in Chapter 3, section 3.5.

4.2.1.2.3 Gateway

The P-NUCLEO-LRWAN3 development board from STMicroelectronics plays a crucial role in the implementation of the proposed IoT-based crop and irrigation monitoring system. Serving as the gateway device, it comprises two boards, as shown in Figure 4.8. The RF module, known as the LRWAN_GS_LF1 LoRa LF band from RisingHF, is equipped with the Semtech SX1301 LF baseband concentrator and two SX1255 radio transceivers, as shown in Figure 4.9 and Figure 4.10. It has an output power of 6 dBm and a sensitivity of -140 dBm at 300 bit/s (ST, 2021b:14), making it well-suited for low-power wide-area network (LPWAN) applications, and the NUCLEO-F746ZG, equipped with the STM32F746ZGT6 Arm Cortex 7 Arm cortex microcontroller, which controls the RF module via the SPI interface, satisfying the requirement stated in Chapter 3, section 3.4.1.

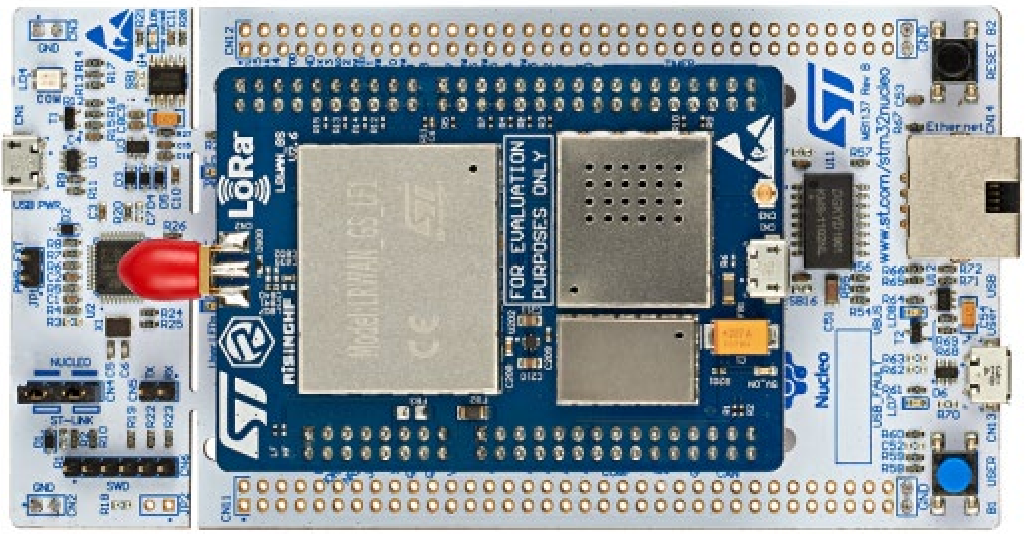

Figure 4.8: **P-NUCLEO-LRWAN2**

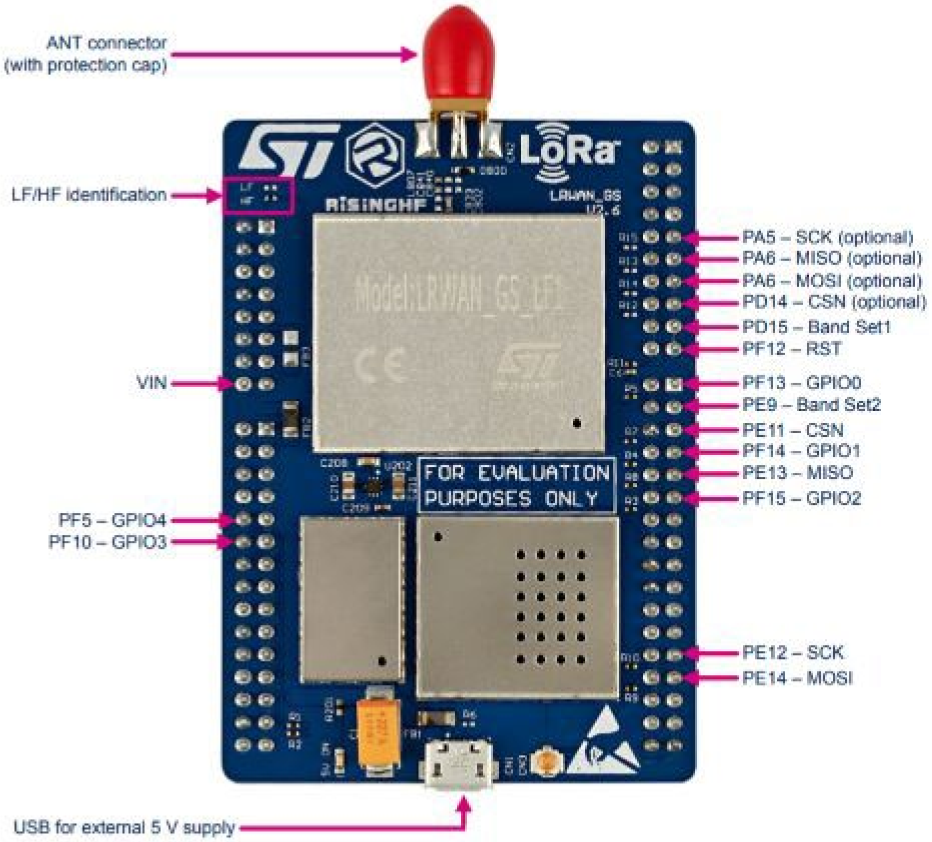

Figure 4.9: Gateway RF Module

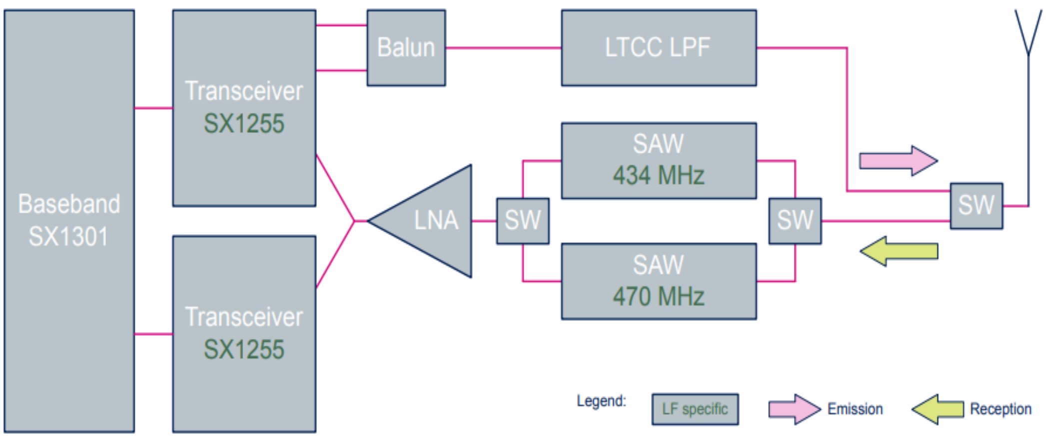

Figure 4.10: RF Module Architecture

As the gateway, the P-NUCLEO-LRWAN3 is responsible for receiving data from the distributed soil moisture sensors employed throughout the agricultural area via the end node and forwarding this data to the Network server. It leverages the long-range and low-power capabilities of the SX1301 and the SX1255 radio transceiver to establish communication links with the sensors, enabling efficient data transmission over extended distances.

The STM32F746ZGT6 microcontroller provides the necessary processing power to handle incoming sensor data, manage network protocols, and interface with the central monitoring and data storage unit. Moreover, the P-NUCLEO-LRWAN3 development board's compatibility with the STM32Cube development ecosystems and the use of AT commands allowed seamless integration into the overall software architecture. This compatibility streamlined the development process.

The integration of the P-NUCLEO-LRWAN3 as the gateway device is crucial for establishing a robust and reliable communication infrastructure, enabling the collection and relay of soil moisture data from deployed sensors. Leveraging the LPWAN capabilities of the board, the system is designed for cost-effective, long-range, and low-power data transmission, specifically tailored for crop monitoring and irrigation system applications. The P-NUCLEO-LRWAN3 serves as a vital component in the prototype design, facilitating seamless data aggregation and contributing to the successful implementation and evaluation of the IoT-based soil moisture monitoring system.

4.2.1.2.4 LoRaWAN Servers and Cloud-Based Storage

he LoRaWAN servers play a crucial role as they function both as a LoRaWAN network and an application server. In their capacity as a LoRaWAN network, these servers enforce the LoRaWAN protocol, ensuring the authenticity and reliability of End Nodes. They effectively eliminate duplicate uplink messages that may arise due to multiple Gateways relaying the same information to the Network Server. Additionally, the LoRaWAN servers play a key role in selecting gateways for transmitting downlink data and issuing Adaptive Data Rate commands. Any transmission failing the authentication process is promptly discarded.

In their role as an application server, these components decrypt messages received from the sensors and perform the inverse operation for downlink messages. Beyond this, the servers diligently store both incoming and outgoing messages. They become instrumental in data analysis, drawing graphs for comprehensive visualisation and aiding further analysis. Together, the LoRaWAN servers and cloud-based storage form a resilient backbone, ensuring secure, reliable, and insightful data handling within our IoT-based soil moisture monitoring system.

There are four types of LoRaWAN networks: public, private, hybrid, and community networks. Each has its advantages and disadvantages. For this study, the Hybrid network model is employed, where the end node, the gateway, and the user application are privately owned, while only the network and application servers are publicly owned.

In this study, the Loriot platform has been selected as the service provider for the LoRaWAN Servers. Loriot is an international IoT company, established in Switzerland in 2015, that provides a hybrid network management system for massive IoT deployments. It supports both LoRaWAN and mioty protocols, enabling a wide range of use cases. Loriot's platform is designed for scalability, resilience, and flexibility, making it suitable for large-scale IoT deployments in various industries. It is one of the most powerful, complete and secure solutions in the market to protect IoT data(Loriot, no date).

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4.2.1.2.4.1 End Node and Gateway Registration on Loriot Platform

To begin using the Loriot platform, registration is the initial step, and there are three options available: the free Community Public Server, Professional Public Server, and Enterprise Private Server. For this study, the free public server option is chosen, although it comes with limitations on the number of end nodes and gateways, as well as restricted features. These limitations are compensated for in the User Application platform of this prototype design.

The following steps were taken to create a free account and register both the end node and the gateway:

- The Cape Town, South Africa server was selected based on the geographical location of this study, as depicted in Figure 4.11.

- Both the end node and gateway were registered with the Loriot network server, as illustrated in Figure 4.12. At this stage, real-time and historical data can be accessed from any device at any time.

To register the gateway, the following information was entered:

- Selected region frequency
- Selected channel plans
- Filled in the MAC address and its location.

To register the end node with the Loriot network server:

- Selected OTAA
- Filled in DevEUI, AppEUI, and AppKey.
- Selected LoRaWAN version

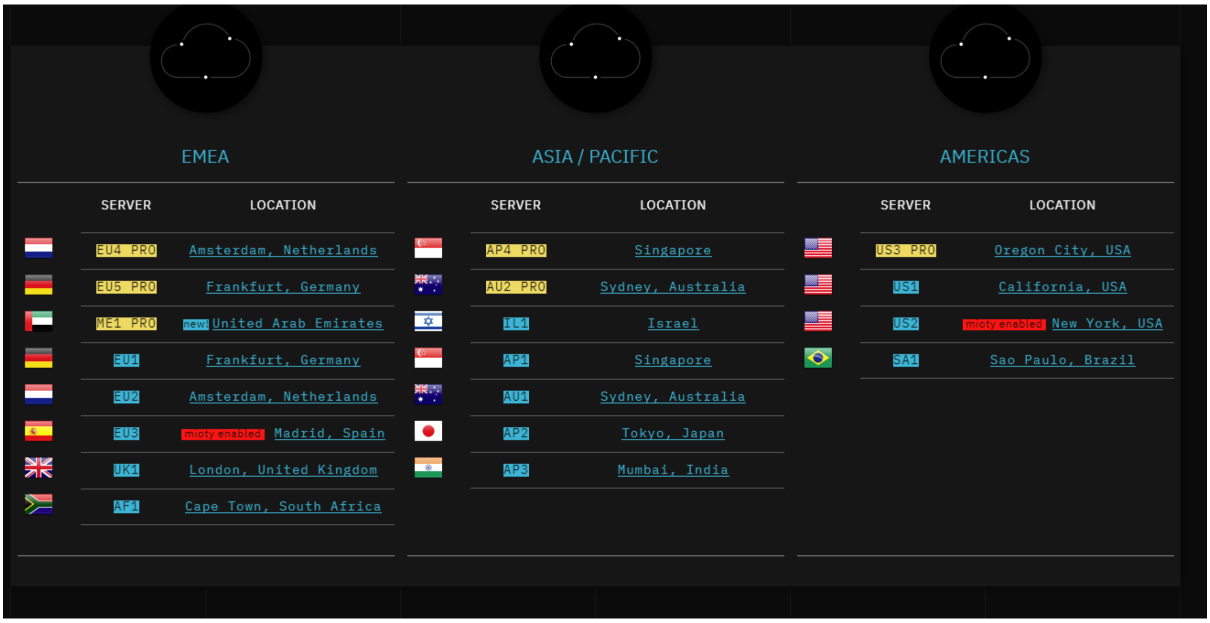

Figure 4.11: Server selection

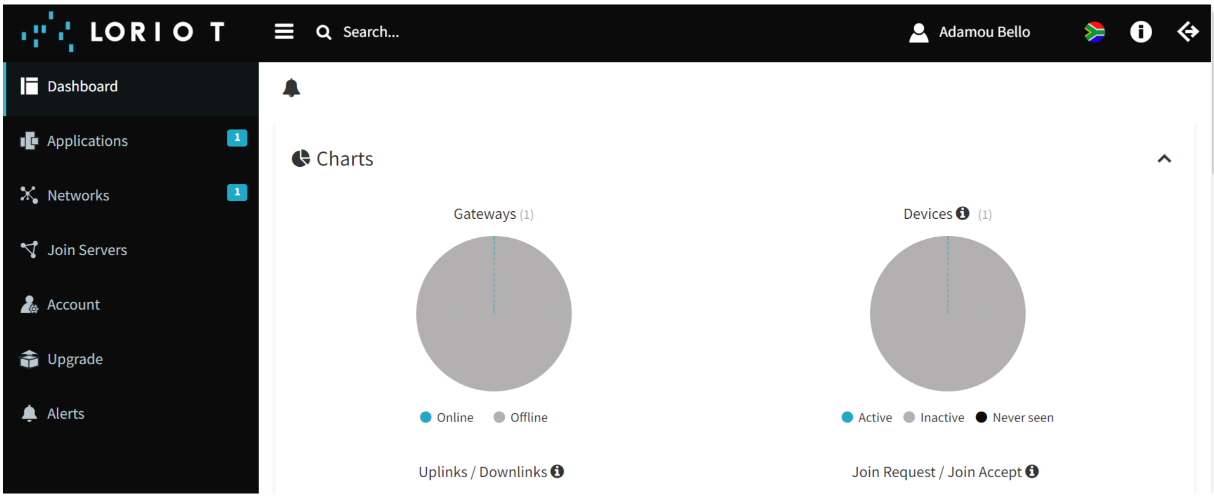

Figure 4.12: Gateway and End Node status

4.2.1.2.5 User Application

Two user applications were developed to enhance the functionality and accessibility of the IoT-based soil moisture monitoring system. The first application is a web-based interface accessible from any device, offering users real-time and historical data. It comprises two main tabs: Environmental Monitoring and Irrigation Control.

- **Environmental Monitoring Tab:**

  This tab displays crucial information such as soil moisture level, battery status, temperature, and irrigation status. Leveraging the soil moisture level, the system autonomously controls the irrigation process. Users can monitor and analyse environmental conditions efficiently, as shown in Figure 4.13.

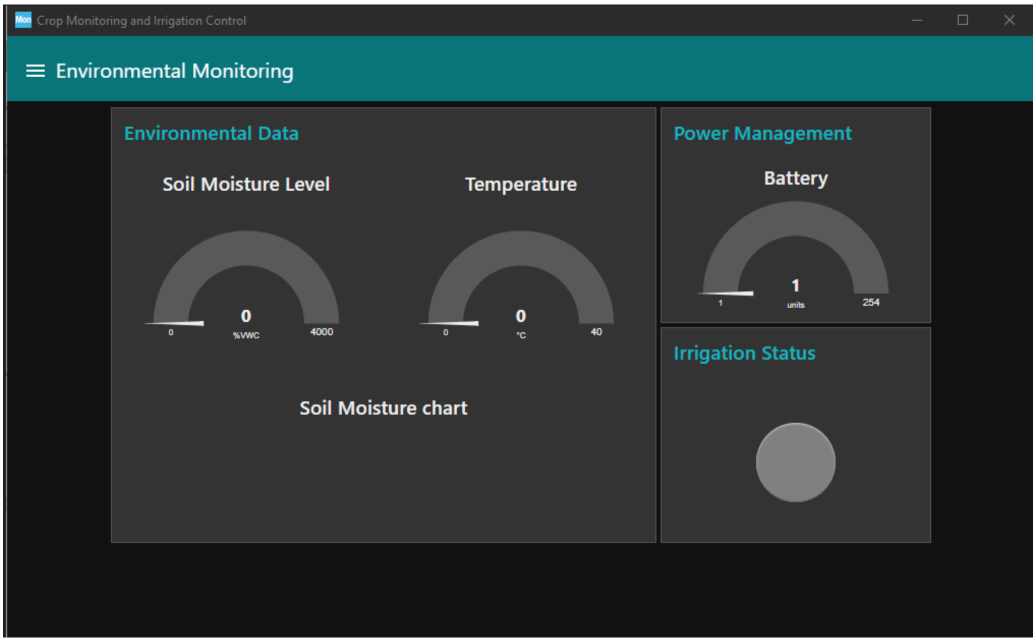

Figure 4.13: Environmental Monitoring

- **Irrigation Control Tab**:
  Providing users with manual control, this tab allows users to initiate irrigation based on their preferences, offering a dual control mechanism for irrigation processes, as shown in Figure 4.14.

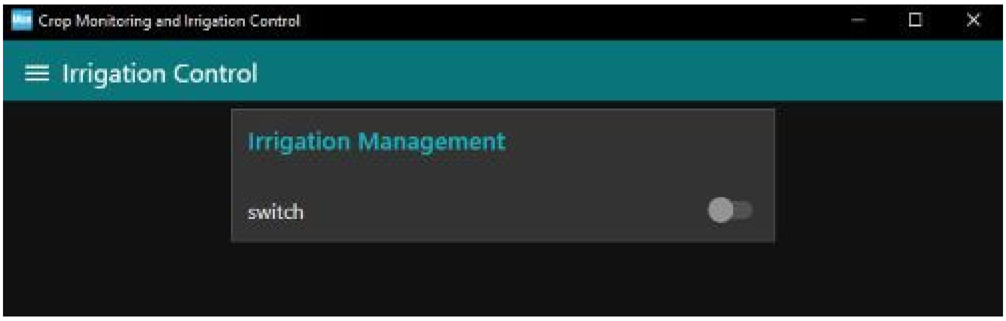

Figure 4.14: Irrigation Control

The second user application is an Android app designed for mobile devices. This app serves as a backup solution in case of server downtimes. While the primary web-based application relies on server connectivity, the Android app ensures users can still control the irrigation system even when the server is temporarily unavailable. This redundancy enhances the system's reliability and ensures uninterrupted irrigation control.

4.2.2 Phase 2: Implementation of IoT Platform

In the implementation phase, configuring the gateway is a pivotal step, where the system requires knowledge of the sender's frequency channel, and the destination port and IP address for the received data. AT commands, which stand for Attention Commands, were utilised via the UART interface to set up the gateway.

Figure 4.15 illustrates the default configuration of the gateway as received from the manufacturer, providing a baseline for subsequent adjustments. Subsequently, Figure 4.16 showcases the AT commands in action, specifically changing the frequency channel to align with the project's requirements. The final configuration for this project, including the updated LoRaWAN server IP address, is depicted in Figure 4.17. These commands, initiated by the characters "AT," allowed for the precise configuration of communication parameters, establishment of connections, and querying of information for the P-NUCLEO-LRWAN3. Once the gateway was successfully configured, all system components seamlessly fell into place, operating cohesively as intended. The system's workflow is elucidated in Figure 4.18.

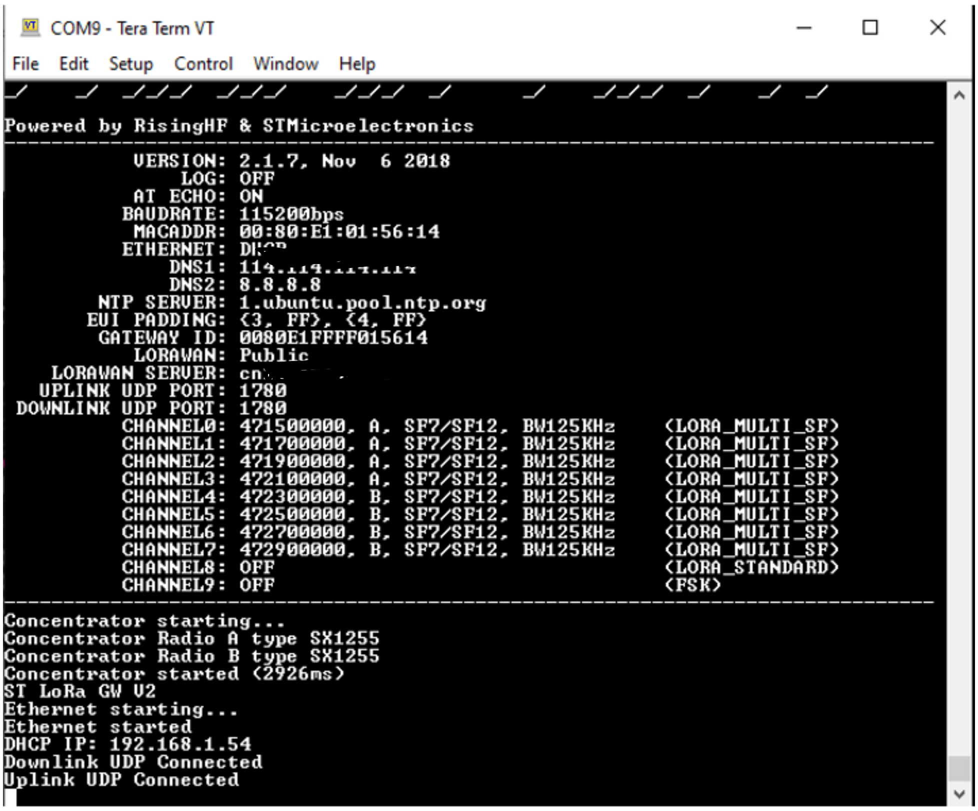

Figure 4.15: **Default Configuration**

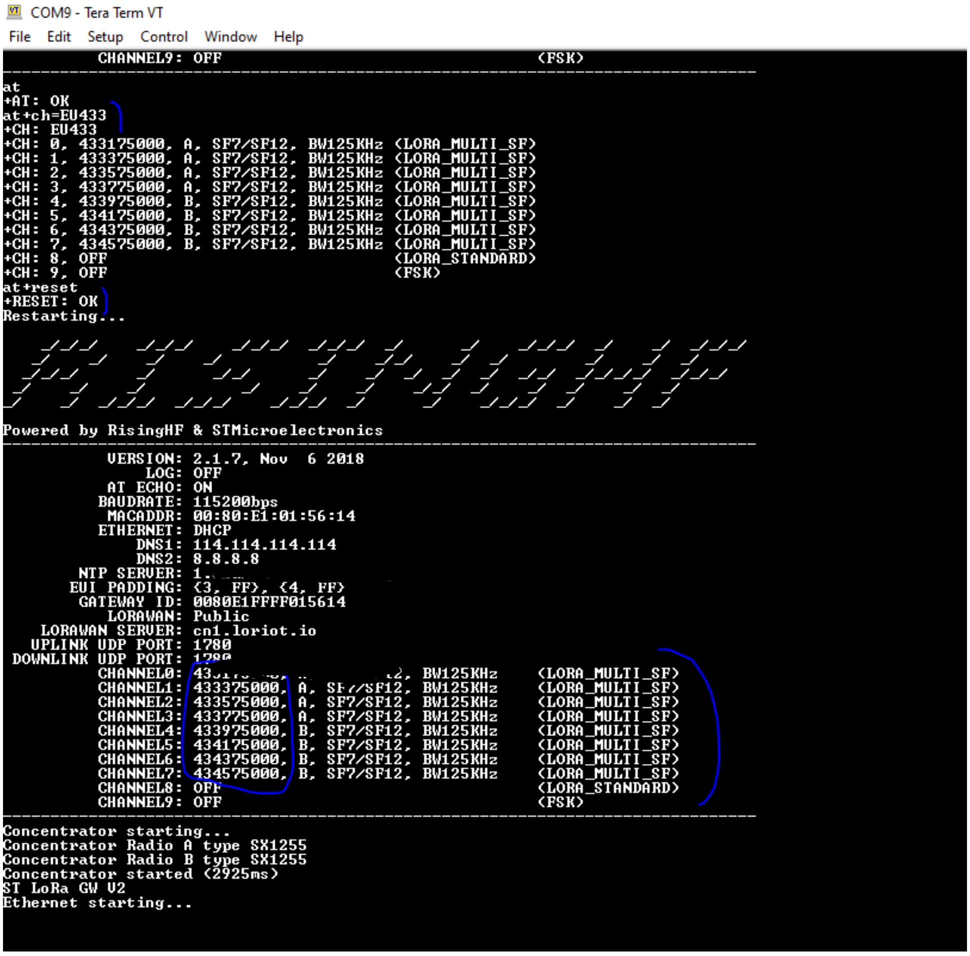

Figure 4.16: Updated Frequency Channel

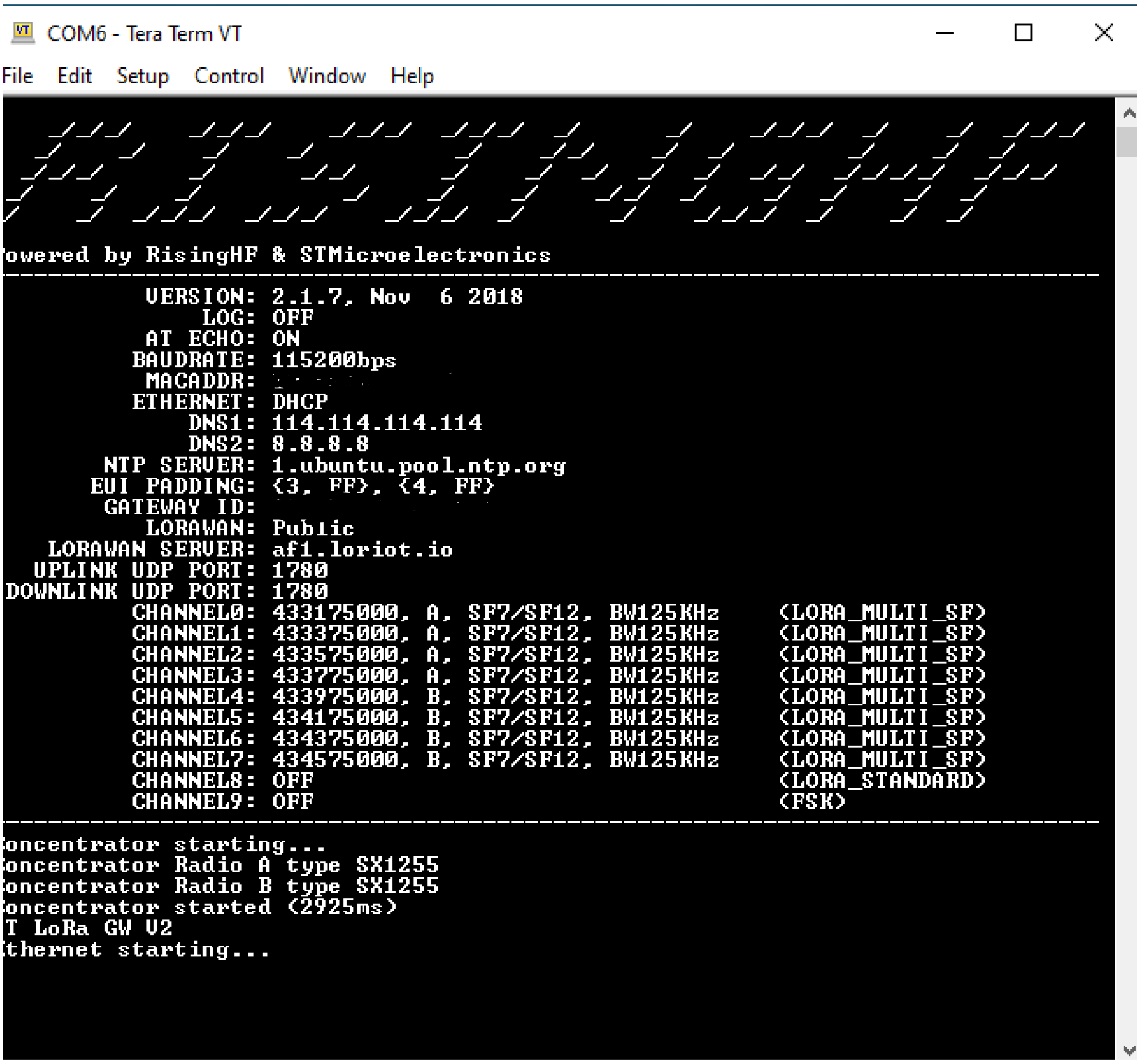

Figure 4.17: Final Configuration

4.2.2.1 Sequence Diagram Role Breakdown

This section provides a detailed breakdown of the roles and interactions depicted in the IoT system implementation sequence diagram, offering insights into the specific functions of each component during the end device activation, soil moisture data transmission, user interaction, device control, and the pivotal role of the soil moisture sensor in the continuous data collection process. Figure 4.18 shows the steps involved in the system's operation and provides a general overview of the workflow.

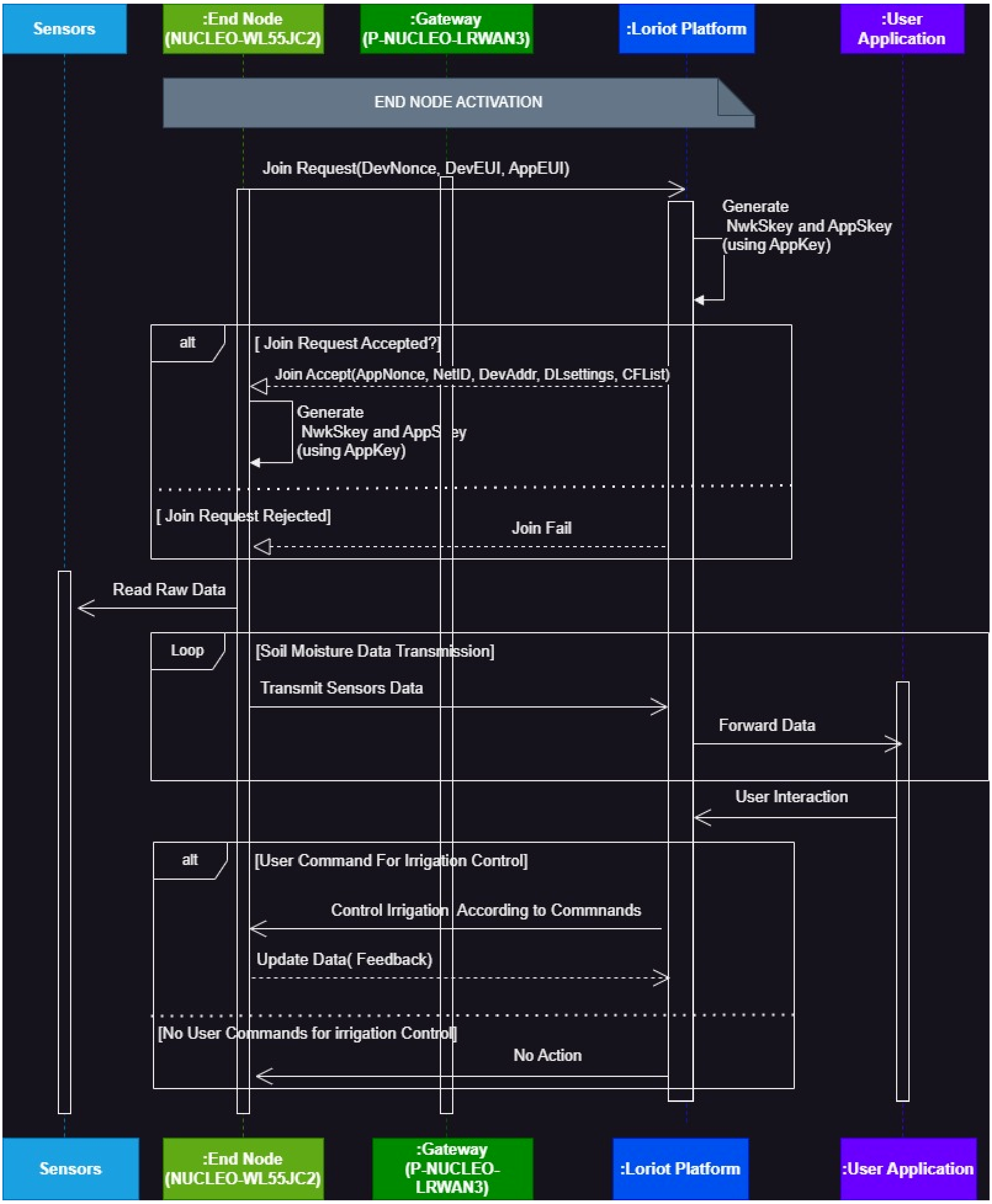

Figure 4.18: IoT System Implementation Sequence Diagram

In a LoRaWAN network, activating an end node is a critical step to ensure successful communication between the device and the network server. This activation process establishes the necessary security credentials and communication parameters that enable the end node to join the network and securely transmit data.

The following sections detail the steps involved in the activation process, data transmission, user interaction and irrigation control.

1. **End Node Activation (Initialisation)**

To join a LoRaWAN network, an End Node must exchange two messages with the Network Server: a join request and a join accept (Alliance, 2018:34).

- The "End Node (NUCLEO-WL55JC2)" initiates the process by sending a "Join Request" message to the "Loriot Platform" (Loriot). This message includes parameters such as DevNonce, DevEUI, and AppEUI.
- Loriot generates the necessary keys (NwKSkey and AppSKey) based on the AppKey.
- If the "Join Request" is accepted, Loriot responds with a "Join Accept" message, including parameters like AppNonce, NetID, DevAddr, DLsettings, and CFList(optional), as shown in Figure 4.19.

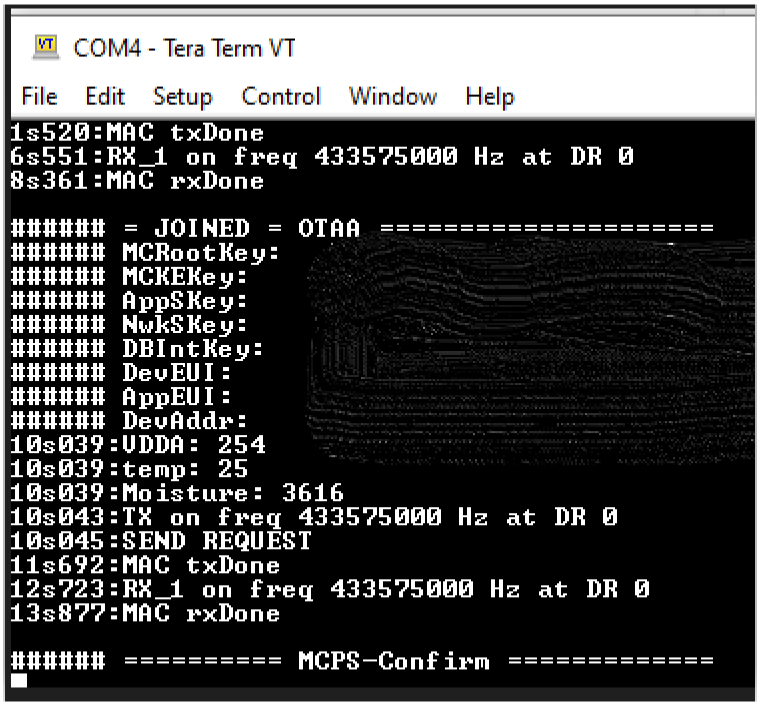

Figure 4.19: **Join request Accepted and Transmission has Started**

- In case of rejection, Loriot sends a "Join Failed" message, as shown in Figure 4.20.

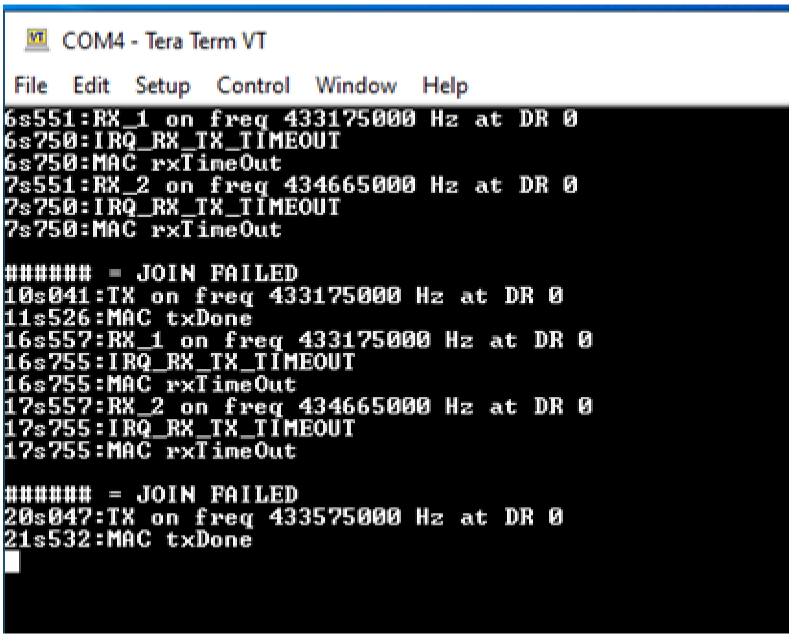

Figure 4.20: Join Request Failed

2. **Sensors Data Transmission:**
   - After successful activation, the “End Node” periodically transmits soil moisture, temperature, and battery data, as shown in Figure 4.19.
3. **User Interaction and Irrigation Control:**
   - The "User Application" interacts with Loriot to control the irrigation system or retrieve data.
   - If user commands involve Irrigation control, Loriot communicates with the "Gateway" to manage the irrigation system. The "End Node" updates data, and Loriot reflects these changes to the "User Application."
4. **Soil Moisture Sensor’s Role:**
   - The "Soil Moisture Sensor" is implicitly involved during the "Soil Moisture Data Transmission" phase, where the "End Node" gathers data from the sensor and transmits it to Loriot.

4.3 Summary

The convergence of IoT and Cloud Computing emerges as a transformative force, potentially revolutionising traditional farming practices. By harnessing cutting-edge technologies, this research aimed to enhance resource utilisation and crop management, contributing to the advancement of smart agriculture. The methodology chosen allowed for the seamless integration of diverse networks, making the way for a scalable and efficient IoT platform. Undoubtedly, the research journey was not without its challenges. Issues related to data security, optimising data sampling for reduced power consumption, component procurement, and the intricate process of getting the end device operational required careful consideration. Retrieving useful data from the Loriot platform and decoding it on the user application added complexity to the implementation process. Despite these challenges, the systematic approach employed ensured the integrity, reliability, and scalability of the developed IoT and cloud computing platforms.

Overcoming these obstacles has contributed to the refinement and improvement of the proposed IoT and Cloud computing system, underscoring the resilience and adaptability of the chosen methodology. The sequence diagrams carefully depicted the breakdown of roles and interactions, providing a clear understanding of how the system operates during End Node activation, data transmission, user interaction, and Irrigation control. This clarity was instrumental in laying the groundwork for the successful implementation and operationalisation of the platform. The next phase of the research will focus on analysing data collected from the implemented system to gain a deeper understanding of its impact on resource utilisation, crop management, and overall agricultural sustainability.

CHAPTER FIVE
SYSTEM VALIDATION AND DATA AVAILABILITY

5.1 Introduction

The success of any IoT-based system, particularly in smart agriculture, relies on its capacity to consistently collect, process, and provide data for real-time decision-making and long-term analysis. This chapter is dedicated to validating the developed IoT platform system and assessing the availability and accuracy of the gathered data.

System validation is essential to ensure that the IoT platform functions as intended, delivering precise and reliable data that farmers and researchers can rely on. This involves thorough testing procedures, such as functional, performance, and user acceptance testing, to verify the seamless operation of all system components, including sensors, end devices, gateways, and user applications.

Data availability is equally important, as it enables continuous monitoring of agricultural conditions and the ability to make informed decisions based on real-time and historical data. This chapter describes the method used to collect, store, and access data using the capabilities of the Loriot platform and the user application interface.

By systematically validating the system and ensuring the availability of high-quality data, this chapter aims to demonstrate the efficacy and reliability of the Smart Agriculture System, thus reinforcing its potential to revolutionise traditional farming practices through technology-driven solutions.

5.2 System Functionality Confirmation

The successful implementation and integration of the developed IoT and cloud computing systems mark a significant milestone in achieving the research objectives. The seamless interaction between system components, from End Node to Gateway and Loriot servers, has resulted in a fully operational system.

The confirmation of successful integration is reflected in the Loriot dashboard, which displays the status of the gateway and the end device as online, contrary to Figure 4.12, which shows offline. Moreover, the uplink and downlink messages were well received, and both the Join Accept and Join Request are visibly shown. Figure 5.1 provides a visual representation of this system's running status, affirming the successful functionality of the developed IoT and Cloud computing system.

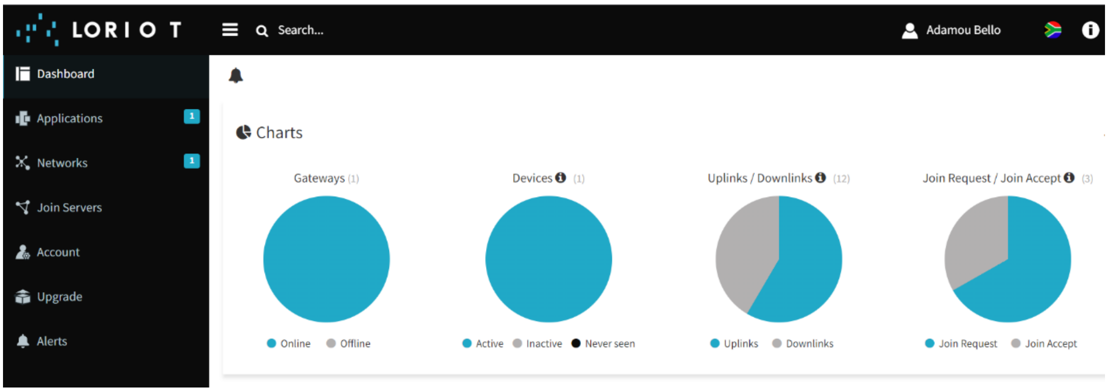

Figure 5.1: System in Running Mode

5.3 Data Availability on the Loriot Platform

The Loriot platform plays a central role in aggregating and managing data transmitted by the End Node. Real-time soil moisture, temperature, and battery level data are gathered through an array of sensors, are efficiently processed and made accessible on the Loriot platform. This data repository serves as a comprehensive resource for monitoring and analysing agricultural conditions.

Figure 5.2 displays the total number of transmitted messages received on the vertical axis, with dates represented on the horizontal axis. On November 11th, the Loriot platform received 661 uplink messages, while 183 downlink messages were transmitted to the end device for irrigation system control. On December 2nd, 273 uplink messages were received, accompanied by 27 downlink messages.

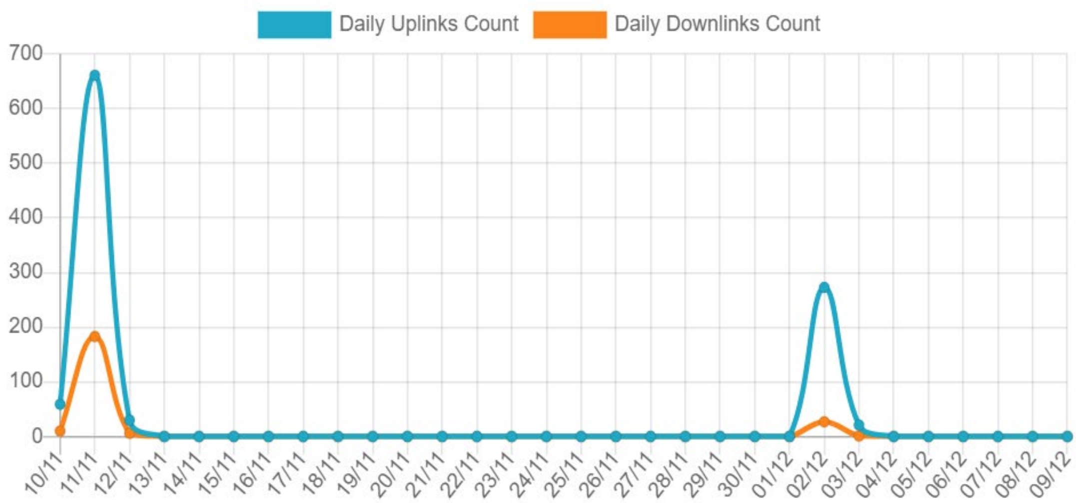

Figure 5.2: Daily Received Messages

Figure 5.3 displays the size of transmitted messages received on the vertical axis in kilobytes, with dates depicted on the horizontal axis. On November 11th, the Loriot platform received 16,623 uplink messages, and 2,610 downlink messages were transmitted to the end device for irrigation system control. On December 2nd, 7,465 uplink messages were received, along with 390 downlink messages.

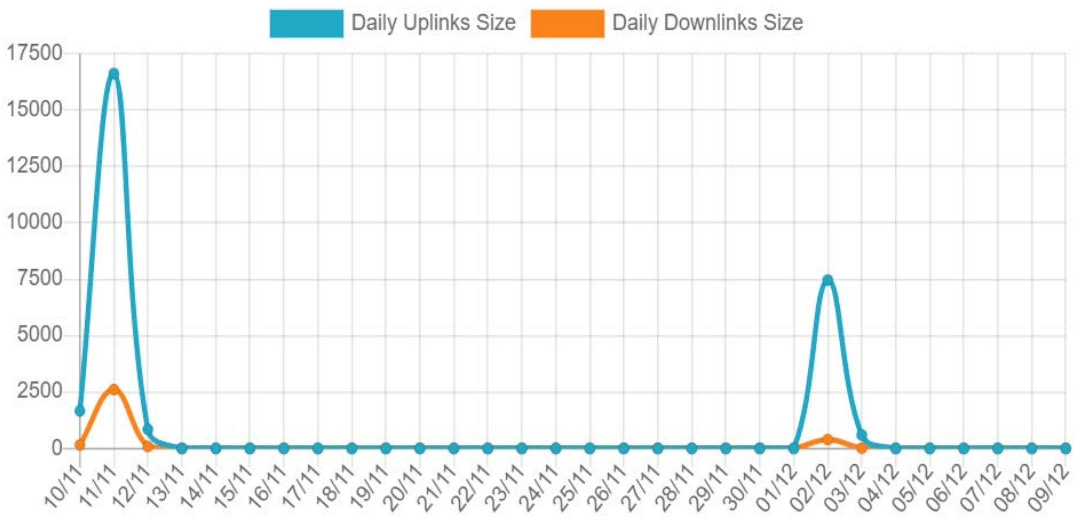

Figure 5.3: **Daily Received Messages in Size**

The historical data, illustrated in Figure 5.4, serves as a valuable record of historical frame data, affirming the robust data availability on the Loriot platform. This visual representation encapsulates the timeline of received frames, offering insights into the consistent and reliable data flow between the end node and the Loriot platform. This historical data provides tangible evidence of the sustained performance and uninterrupted data availability within the IoT and cloud computing system.

Device EUI	FCntUp	Time	Port	Data
[redacted]	10	7 days ago	2	00 0e 1f 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
[redacted]	9	7 days ago	2	00 0e 1e 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
[redacted]	8	7 days ago	2	00 0e 1e 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
[redacted]	7	7 days ago	2	00 0e 1d 18 01 f4 fe 3e 09 0d 05 03 ab 00 00
[redacted]	6	7 days ago	2	00 0e 1f 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
[redacted]	5	7 days ago	2	00 0e 21 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
[redacted]	4	7 days ago	2	00 0e 1c 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
[redacted]	3	7 days ago	2	00 0e 1d 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
[redacted]	2	7 days ago	2	00 0e 1d 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
[redacted]	1	7 days ago	2	00 0e 1c 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
[redacted]	11	7 days ago	2	00 0e 1e 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
[redacted]	10	7 days ago	2	00 0e 1a 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
[redacted]	9	7 days ago	2	00 0e 21 19 01 f4 fe 3e 09 0d 05 03 ab 00 00

Figure 5.4: Received Frame Data

The ability to receive, process, and interpret data from various devices is crucial in the realm of IoT applications. This data forms the foundation for informed decision-making and effective operational management. Below is a detailed explanation of the components of the received frame data, which are vital for assessing device performance and network stability. Each column of Figure 5.4 represents a distinct aspect of the data essential for these evaluations:

- **Device EUI:**
  Device identifier associated with uplink transmissions received by the Gateway.
- **FCntUp:**
  LoRaWAN frame counter (FCntUp) for uplink messages. It tracks the number of messages sent by the End Node since its last reset, used for monitoring data sequence integrity.
- **Time:**
  This value indicates how long the Gateway registered the message arrival.
- **Port:**

This is the LoRaWAN frame Port (FPort) number used by the End Node for this uplink message.

- **Data:**

  This is the hexadecimal representation of the End Node's uplink payload, which includes temperature, battery level, and soil moisture level

5.4 User Application Accessibility

The user application, designed to provide farmers with insights into soil conditions and crop health, successfully interfaces with the Loriot platform. Users can access real-time data, historical trends, and personalised recommendations through a user-friendly interface available on both desktop and mobile devices, as illustrated in Figure 5.5.

Additionally, the End Node is equipped with LEDs designed to be particularly useful in offline scenarios when the user is in a remote location with no internet connection:

- **LED1 (Blue):**

  This light will flash to indicate the reception of data by the end device.

- **LED2 (Green):**

  This light will flash when the end device transmits data to the gateway.

- **LED3 (Red):**

  Informs the user about the irrigation status; it turns on when irrigation is active and turns off when irrigation is inactive.

5.5 Verification Through User Interaction

To ensure the reliability and accuracy of collected data, rigorous testing and validation procedures are seamlessly integrated into the system development lifecycle. The verification of user interactions with the system, encompassing irrigation control and data retrieval, confirms alignment with the intended functionalities.

- **Soil Very Dry:**

  Figure 5.5 captured a scenario where the soil was extremely dry, prompting the irrigation system to be turned on, as indicated by the yellow LED on the GUI.

- **Soil Dry:**

  In Figure 5.6, the soil was dry, prompting the irrigation system to remain on. The yellow LED on the GUI reflects this status, providing a clear visual indicator.

- **Soil Very Wet:**

Figure 5.7 highlights a situation where the soil was saturated with moisture, resulting in the irrigation system being off. This is represented by the white LED on the GUI, ensuring users are informed about the current soil conditions.

Figure 5.5, Figure 5.6, and Figure 5.7 contain charts. The moisture level is indicated on the vertical Y-axis, while the horizontal X-axis represents time. These graphs provide a clear visualisation of how the moisture level fluctuates over a specific period. The duration at which different moisture levels were maintained is effectively illustrated. This information is crucial for understanding the environmental conditions and their changes over time.

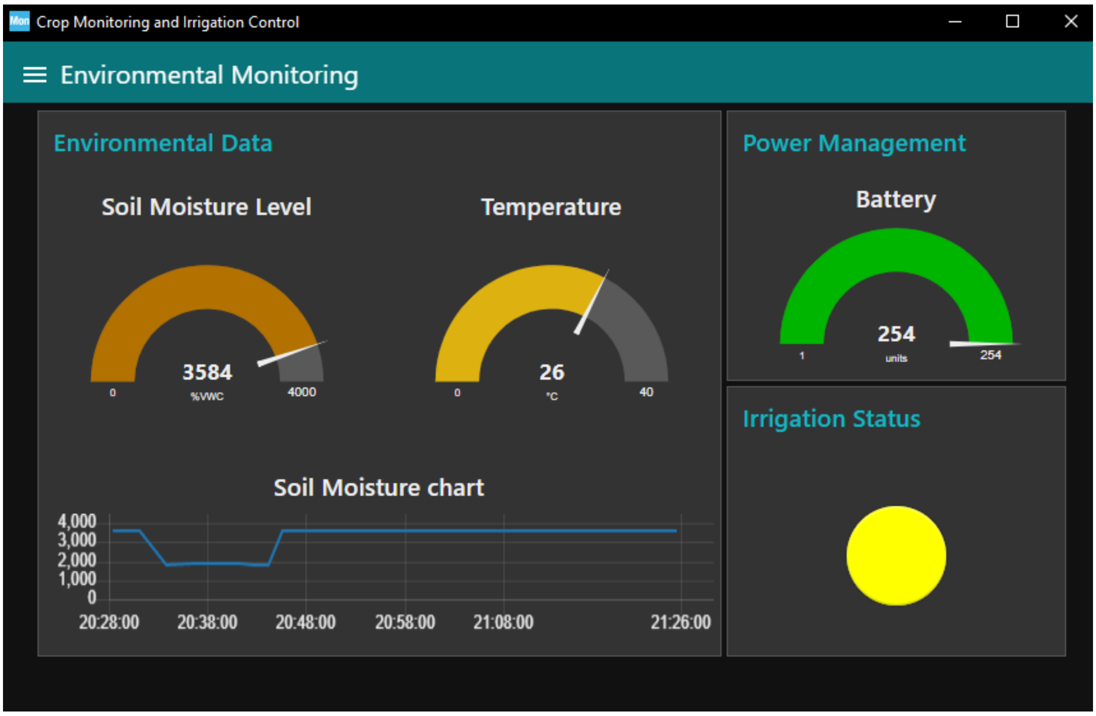

Figure 5.5: Soil Very Dry

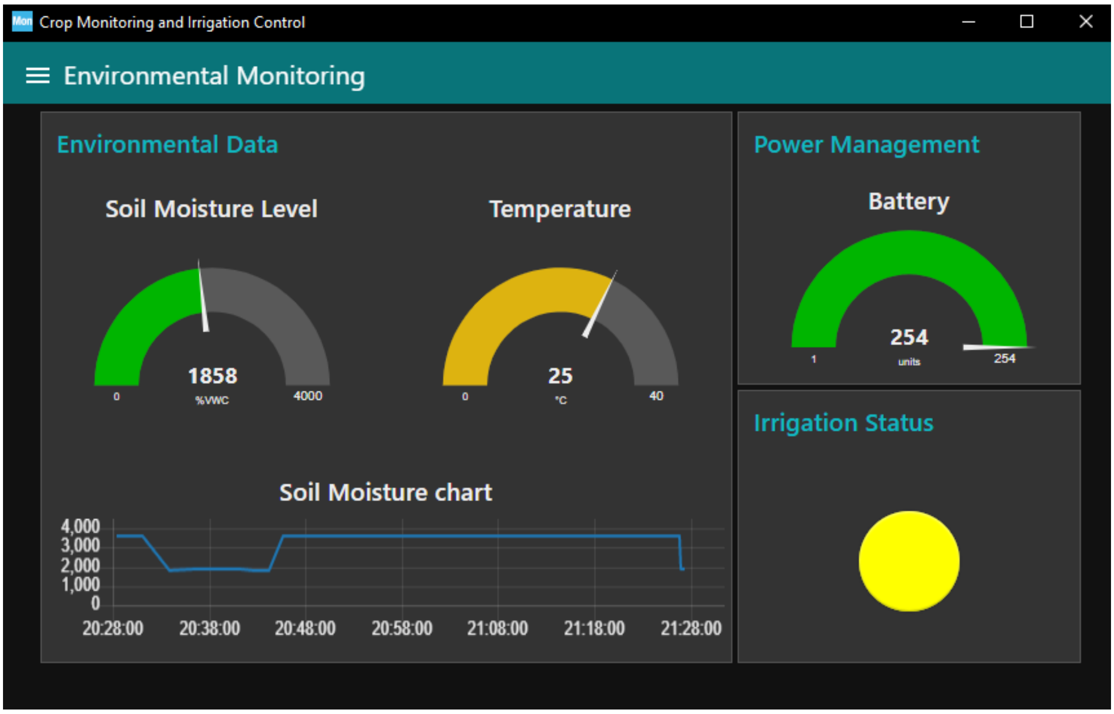

Figure 5.6: Soil Dry

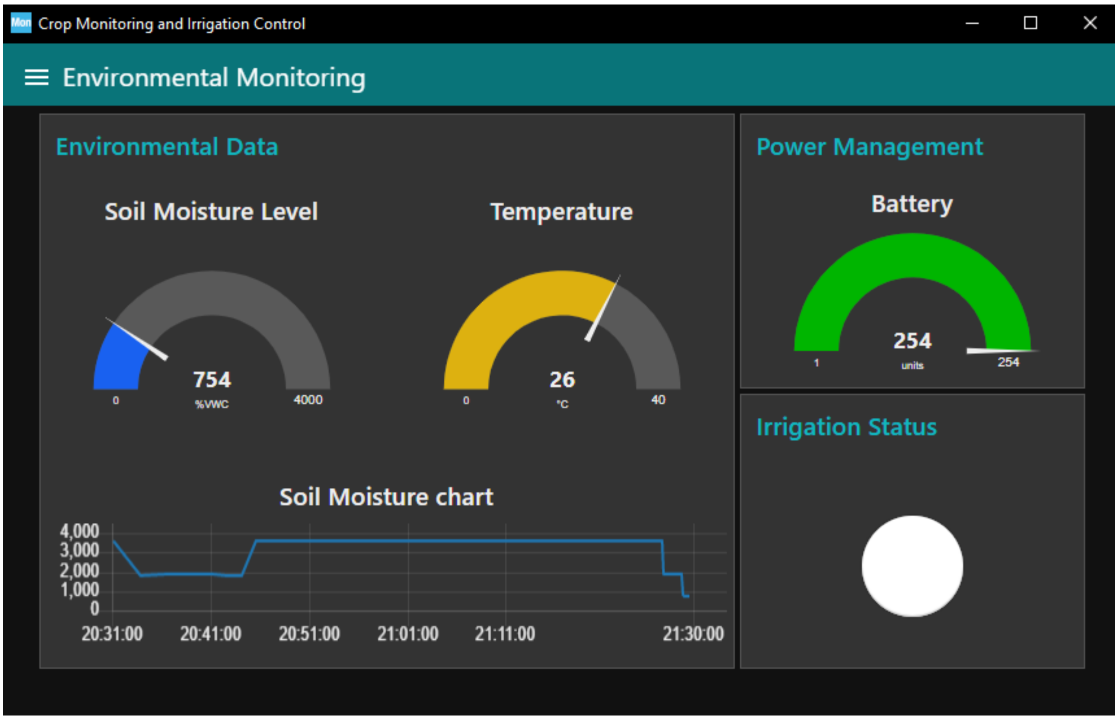

Figure 5.7: Soil Very Wet

In the context of user-initiated irrigation control, the system features a manual switch that empowers users to toggle the irrigation status at their discretion.

- **Switch On:**

Figure 5.8 illustrates a moment when the user activates the irrigation manually by turning the switch on. This deliberate action is visually represented by the illuminated blue LED on the graphical user interface (GUI). The vivid blue light signals that the irrigation system is actively delivering water to the crops. This activation is also confirmed by the Android App, as depicted in Figure 5.9.

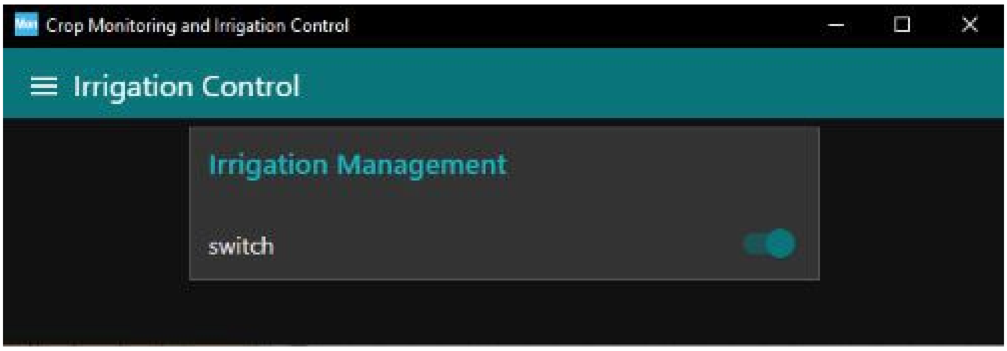

Figure 5.8: Irrigation System Manually Switched On

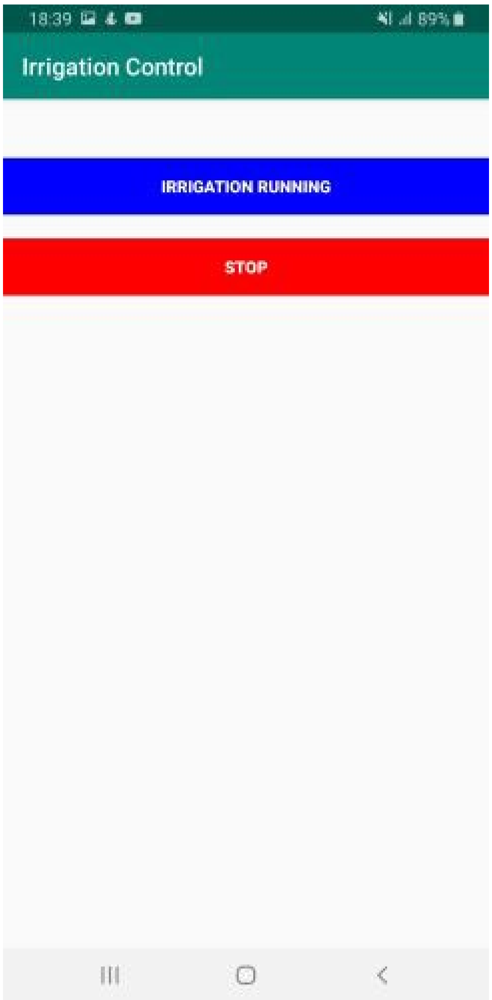

Figure 5.9: Irrigation Running

- **Switch Off:**

  Conversely, if the user decides to deactivate the irrigation manually by turning the switch off, the GUI reflects this choice through a grey LED, as shown in Figure 4.14. The grey light indicates that the irrigation system is in an inactive state, withholding water supply to the crops. This deactivation is also confirmed by The Android App, as depicted in Figure 5.10

Figure 5.10: **Irrigation Not Running**

5.6 Conclusion of System Validation

In conclusion, the successful operation of the IoT and cloud computing system, coupled with the availability of data on both the Loriot platform and user application, validates the robustness and efficacy of the implemented IoT and cloud computing solutions. This operational success sets the stage for comprehensive data analysis and continued refinement of the system based on user feedback and evolving agricultural needs.

CHAPTER SIX
CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

After conducting a thorough investigation, this research has provided essential insights and contributions to the field of smart agriculture, by seamlessly integrating IoT and cloud computing technologies. The key findings, which were established after rigorous testing and validation procedures, confirm the accuracy and reliability of the system's collected data. The operational success, verified through user interactions and data availability on both the Loriot platform and user application, highlights the effectiveness and robustness of the implemented solution.

The research has contributed to the advancement of smart agriculture by introducing an enhanced feature, equipping the end device with edge-level decision-making capabilities for irrigation control. This advanced feature ensures system resilience, enabling autonomous control in scenarios where internet connectivity is compromised or lacking in remote locations.

The smart agriculture system developed in this research not only facilitates efficient crop management and resource utilisation for farmers but also carries broader implications for scientific research. Data stored in the cloud serves as a valuable resource for scientists studying the characteristics of specific crops or regions. In situations where farmers are confronted with phenomena they do not fully comprehend, cloud-stored data becomes an invaluable asset. Researchers can leverage this data remotely to gain insights into and address issues faced by farmers, eliminating the need for specialists to visit the fields for raw data collection physically. This implication extends beyond localised problem-solving, offering a scalable and accessible means for collaborative research and informed decision-making in the agricultural domain.

6.2 Dissertation Deliverables

This section summarises the work performed and the key findings in each chapter to accomplish the research study's aims and objectives.

- **Chapter 2: Literature Review**

  Identified a gap in developing an integrated IoT and cloud computing platform for smart agriculture. Reviewed existing research on IoT applications in agriculture, highlighting the need for more comprehensive solutions that address water loss, crop development, and productivity for diverse farming contexts.

- **Chapter 3: Theoretical Framework**
  Provided a theoretical foundation for the platform, covering key concepts such as sensors, processors, data storage, and network technologies and protocols. Delved into the principles of integration, highlighting how these components can be selected to work together to form a cohesive system. Explored the roles of LoRa and LoRaWAN in facilitating long-range, low-power communication within the smart agriculture framework.

- **Chapter 4: System Development and Implementation**
  Described the research design and methods used to develop and test the integrated IoT and cloud computing platform. Detailed the processes for selecting and implementing sensors, data storage solutions, and network technologies. Explained the criteria for evaluating the system's effectiveness in reducing water loss, improving crop development, and maximising productivity.

- **Chapter 5: System Validation and Data Availability**
  Summarised the outcomes of system validation tests and data availability assessments. Presented the results of field trials, demonstrating the platform's ability to collect, transmit, and store data efficiently. Highlighted the system's reliability and effectiveness in various agricultural scenarios.

- **Chapter 6: Conclusion and Recommendations**
  Concluded the dissertation by summarising the key contributions of the research. Provided recommendations for implementing the integrated IoT and cloud computing platform in real-world agricultural settings. Suggested further improvements to enhance the system's performance and scalability.

6.3 Recommendations for Future Work

Three areas can be focused on to improve the system:

- **Enhanced Edge Decision-Making:**
  Avenues for further enhancing the end device's edge-level decision-making capabilities can be explored. This could involve the integration of advanced machine learning algorithms or other artificial intelligence techniques to allow the end device to adapt and make more sophisticated decisions based on evolving conditions.

- **Integration of Additional Sensors:**
  Incorporating additional sensors can be considered to broaden the scope of data collection. For example, integrating weather sensors or pest detection devices can provide a more comprehensive understanding of the environmental factors impacting crop health, allowing for more precise and proactive agricultural management.

- **User Interface Enhancements:**
  The Loriot platform's user interface and the user application can be continuously refined. User feedback can be gathered to identify areas for improvement, focusing on user experience, accessibility, and the presentation of meaningful insights.

REFERENCES

Adla, S. *et al.* (2020) 'Laboratory calibration and performance evaluation of low-cost capacitive and very low-cost resistive soil moisture sensors', *Sensors (Switzerland)*, 20(2). Available at: https://doi.org/10.3390/s20020363.

Alliance, L. (2018) *LoRaWAN 1.0.3 Specification*. Available at: https://lora-alliance.org/resource_hub/lorawan-specification-v1-0-3/ (Accessed: 10 November 2022).

Alliance, L. (2021) *RP2-1.0.3 LoRaWAN® Regional Parameters - LoRa Alliance®*. Available at: https://lora-alliance.org/resource_hub/rp2-1-0-3-lorawan-regional-parameters/ (Accessed: 15 October 2023).

Alliance, L. (no date) *About LoRa Alliance® - LoRa Alliance®*. Available at: https://lora-alliance.org/about-lora-alliance/ (Accessed: 15 October 2023).

Bahashwan, A.A.O. and Manickam, S. (2019) 'A brief review of messaging protocol standards for Internet of Things (IoT)', *Journal of Cyber Security and Mobility*, 8(1), pp. 1–13. Available at: https://doi.org/10.13052/jcsm2245-1439.811.

Biradar, H.B. and Shabadi, L. (2017) 'Review on IOT based multidisciplinary models for smart farming', *RTEICT 2017 - 2nd IEEE International Conference on Recent Trends in Electronics, Information and Communication Technology, Proceedings*, 2018-Janua, pp. 1923–1926. Available at: https://doi.org/10.1109/RTEICT.2017.8256932.

Chowdhury, S., Sen, S. and Janardhanan, S. (2022) 'Comparative Analysis and Calibration of Low Cost Resistive and Capacitive Soil Moisture Sensor'. Available at: http://arxiv.org/abs/2210.03019.

Debauche, O. *et al.* (2022) 'Cloud and distributed architectures for data management in agriculture 4.0: Review and future trends', *Journal of King Saud University - Computer and Information Sciences*, 34(9), pp. 7494–7514. Available at: https://doi.org/10.1016/j.jksuci.2021.09.015.

DFRobot (no date) *SKU:SEN0308*. Available at: https://wiki.dfrobot.com/Waterproof_Capacitive_Soil_Moisture_Sensor_SKU_SEN0308 (Accessed: 20 June 2023).

Dupont, Corentin *et al.* (2018) 'An open IoT platform to promote eco-sustainable innovation in Western Africa: Real urban and rural testbeds', *Wireless Communications and Mobile Computing*, 2018. Available at: https://doi.org/10.1155/2018/1028578.

FAO (2009) *How to Feed the World in 2050*. Available at: http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf (Accessed: 4 July 2021).

IETF (no date) *The Constrained Application Protocol (CoAP)*. Available at: https://datatracker.ietf.org/doc/html/rfc7252 (Accessed: 10 August 2024).

Kaur, H., Shukla, A.K. and Singh, H. (2022) 'Review of IoT Technologies used in Agriculture', *2022 2nd International Conference on Advance Computing and Innovative Technologies in Engineering, ICACITE 2022*, pp. 1007–1011. Available at: https://doi.org/10.1109/ICACITE53722.2022.9823520.

Klaina, H. *et al.* (2022) 'Analysis of low power wide area network wireless technologies in smart agriculture for large-scale farm monitoring and tractor communications', *Measurement: Journal of the International Measurement Confederation*, 187(October 2021). Available at: https://doi.org/10.1016/j.measurement.2021.110231.

LoRa Alliance (2020) 'LoRaWAN 1.0.4 Specification Package', *LoRaAlliance*, pp. 1–90. Available at: https://lora-alliance.org/resource_hub/lorawan-104-specification-package/ (Accessed: 10 November 2022).

Loriot (no date) *About*. Available at: https://www.loriot.io/about.html (Accessed: 20 May 2023).

Moraes, T. *et al.* (2019) 'Performance Comparison of IoT Communication Protocols', in *2019 IEEE INTERNATIONAL CONFERENCE ON SYSTEMS, MAN AND CYBERNETICS (SMC)*. NEW YORK: IEEE, pp. 3249–3254. Available at: https://doi.org/10.1109/SMC.2019.8914552.

MQTT (no date) *MQTT: The Standard for IoT Messaging*. Available at: https://mqtt.org/ (Accessed: 6 August 2024).

Nageswara Rao, R. and Sridhar, B. (2018) 'IoT based smart crop-field monitoring and automation irrigation system', *Proceedings of the 2nd International Conference on Inventive Systems and Control, ICISC 2018*, (Icisc), pp. 478–483. Available at: https://doi.org/10.1109/ICISC.2018.8399118.

Navarro, E., Costa, N. and Pereira, A. (2020) 'A Systematic Review of IoT Solutions for Smart Farming', *Sensors*, 20(15). Available at: https://doi.org/10.3390/s20154231.

Pagano, A. *et al.* (2023) 'A Survey on LoRa for Smart Agriculture: Current Trends and Future Perspectives', *IEEE Internet of Things Journal*, 10(4), pp. 3664–3679. Available at: https://doi.org/10.1109/JIOT.2022.3230505.

Pathmudi, V.R. *et al.* (2023) 'A systematic review of IoT technologies and their constituents for smart and sustainable agriculture applications', *Scientific African*, 19, p. e01577. Available at: https://doi.org/10.1016/j.sciaf.2023.e01577.

Placidi, P. *et al.* (2022) 'Capacitive Low-Cost System for Soil Water Content Measurement in the IoT Precision Agriculture', *Conference Record - IEEE Instrumentation and Measurement Technology Conference*, pp. 1–6. Available at: https://doi.org/10.1109/I2MTC48687.2022.9806691.

Rajalakshmi, P. and Devi Mahalakshmi, S. (2016) 'IOT based crop-field monitoring and irrigation automation', *Proceedings of the 10th International Conference on Intelligent Systems and Control, ISCO 2016* [Preprint]. Available at: https://doi.org/10.1109/ISCO.2016.7726900.

Ramachandran, V. *et al.* (2022) 'Exploiting IoT and Its Enabled Technologies for Irrigation Needs in Agriculture', *Water*, 14(5), pp. 1–21.

Semtech (2015) *LoRa Modulation Basics*, *Semtech Technique Paper*. Available at: https://semtech.my.salesforce.com/sfc/p/#E0000000JelG/a/2R0000001OJa/2BF2MTeiqIwkmxkcjjDZzalPUGlJ76lLdqiv.30prH8 (Accessed: 1 November 2022).

Semtech (2017) *Application Note : MCU Requirements for LoRaWAN ™*. Available at: https://www.semtech.com/products/wireless-rf/lora-connect/sx1262 (Accessed: 20 March 2023).

Semtech (2019a) 'An In-depth Look at LoRaWAN Class A Devices', *Semtech Technical Paper*, (November), p. 12. Available at: https://lora-developers.semtech.com/uploads/documents/files/LoRaWAN_Class_C_Devices_In_Depth_Downloadable.pdf (Accessed: 10 August 2023).

Semtech (2019b) 'LoRa and LoRaWAN: A technical Overview', *Semtech*, (December 2019), p. 26. Available at: https://lora-developers.semtech.com/uploads/documents/files/LoRa_and_LoRaWAN-A_Tech_Overview-Downloadable.pdf (Accessed: 6 October 2023).

Semtech (2019c) *SX1272/73 - 860 MHz to 1020 MHz Low Power Long Range Transceiver | Semtech*. Available at: https://www.semtech.com/products/wireless-rf/lora-connect/sx1272 (Accessed: 1 November 2022).

Semtech (2021) *SX1261/2 Long Range, Low Power, sub-GHz RF Transceiver*. Available at: https://www.semtech.com/products/wireless-rf/lora-connect/sx1261 (Accessed: 10 September 2023).

Sidna, J. *et al.* (2020) 'Analysis and evaluation of communication protocols for iot applications', *ACM International Conference Proceeding Series*, (December), pp. 257–262. Available at: https://doi.org/10.1145/3419604.3419754.

Singh, K. *et al.* (2019) 'IoT based approach for smart irrigation system suited to multiple crop cultivation', *International Journal of Engineering Research and Technology*, 12(3), pp. 357–363.

ST (2021a) *User Manual*, *STMicroelectronics*. Available at: https://www.st.com/resource/en/user_manual/um2592-stm32wl-nucleo64-board-mb1389-stmicroelectronics.pdf (Accessed: 2 February 2023).

ST (2021b) *User manual Getting started with the P-NUCLEO-LRWAN2 and P-NUCLEO-LRWAN3 starter packs*. Available at: https://www.st.com/resource/en/user_manual/um2587-getting-started-with-the-pnucleolrwan2-and-pnucleolrwan3-starter-packs-stmicroelectronics.pdf (Accessed: 25 November 2022).

STMicroelectronics (2023) *STM32WL5x advanced Arm®-based 32-bit MCUs with sub-GHz radio solution*, *STMicroelectronics*. Available at: https://www.st.com/resource/en/reference_manual/rm0453-stm32wl5x-advanced-armbased-32bit-mcus-with-subghz-radio-solution-stmicroelectronics.pdf (Accessed: 29 April 2023).

United Nations Development Programme (2021) *Sustainable Development Goals | United Nations Development Programme*, *United Nations Development Programme*. Available at: https://www.undp.org/sustainable-development-goals#zero-hunger (Accessed: 4 July 2021).

Verenigde Naties (2019) *9.7 billion on Earth by 2050, but growth rate slowing, says new UN population report*, *UN News, Economic Development*. Available at: https://news.un.org/en/story/2019/06/1040621 (Accessed: 4 July 2021).

Vij, A. *et al.* (2020) 'IoT and Machine Learning Approaches for Automation of Farm Irrigation System', *Procedia Computer Science*, 167(2019), pp. 1250–1257. Available at: https://doi.org/10.1016/j.procs.2020.03.440.

Viswanatha, V. *et al.* (2022) 'Implementation of IoT in Agriculture : A Scientific Approach for Smart Irrigation', *2022 IEEE 2nd Mysore Sub Section International Conference (MysuruCon)*, pp. 1–6. Available at: https://doi.org/10.1109/MysuruCon55714.2022.9972734.

Water and Climate Change (2020). Available at: https://www.who.int/news/item/17-03-2020-water-and-climate-change (Accessed: 11 September 2021).