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Remote Water Monitoring System with a LoRa-Based Solution

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Report submitted in partial fulfilment of the requirements of the module Project (E) 448 for the degree Baccalaureus in Engineering in the Department of Electrical and Electronic Engineering at Stellenbosch University.

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Abstract

English

This project aims to design, develop and implement a remote water monitoring system by using LoRa as communication protocol. Livestock farmers have to drive from camp to camp each day, merely to check trough water levels, which is tedious, time consuming and ineffective. This problem is addressed by creating a complete and functional monitoring system, consisting of field devices and a central receiver, indicating results to the user and alerting them when a trough is empty. This is done through schematic and PCB design, component selection, assembly and software development for each. Enclosures and mounts were designed. Functionality tests were performed, measuring range, transmit power and power consumption, before the system was implemented and run on a farm near Swellendam, Western Cape, confirming full functional operation.

Afrikaans

Die doel van hierdie projek is om 'n langafstand water monitering sisteem te ontwerp, ontwikkel en te implementeer. Veeboere moet elke dag van kraal tot kraal gaan om te kyk of daar nog water in krippe op die plaas is, wat frustrerend, tydrowend en oneffektief is. Hierdie probleem word aangespreek deur die skepping van 'n volle en funksionele moniteringsisteem wat bestaan uit veldtoestelle en 'n sentrale ontvanger wat metings aan die verbruiker kommunikeer en hul waarsku as 'n krip leeg is. Hierdie word bereik deur die ontwerp van stroombaanskemas en gedrukte stroombaan borde, komponent seleksie, samestelling en sagteware ontwikkeling vir elk. Funksionele toetse was gedoen, waar die omvang, oorseinkrag en kragsverbruik gemeet was, voordat die sisteem geimplementeer was op 'n plaas naby aan Swellendam, Wes-Kaap, waar volle funksionele werking van die sisteem bevestig is.

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Nomenclature

Variables and functions

f_{op}	Operating frequency, 868 MHz
f_r	Resonant frequency
Z	Impedance
j	Imaginary number
ω	Angular frequency
C	Capacitance
L	Inductance
R	Resistance

Acronyms and abbreviations

AC	Alternating Current
ACK	Acknowledge
BPSK	Binary Phase Shift Keying
CRC	Cyclic Redundancy Check
CSS	Chirp Spread Spectrum
DBPSK	Differential Binary Phase Shift Keying
DIP	Dual In-Line Package
DL	Down-Link
DMA	Direct Memory Access
EC-GSM-IoT	Extended Coverage Global System for Mobile Communications Internet of Things
eGPRS	Enhanced General Packet Radio Service
EMI	Electromagnetic Interference
EN	Enable
ESR	Equivalent Series Resistance
FOTA	Firmware Over The Air
GFSK	Gaussian Frequency Shift Keying
GMSK	Gaussian Minimum Shift Keying
GND	Ground
GPIO	General-Purpose Input/Output
GSM	Global System for Mobile Communications
HAL	Hardware Abstraction Layer
HAT	Hardware Attached on Top
HDMI	High-Definition Multimedia Interface
HSE	High-Speed External Oscillator
IoT	Internet of Things
IP	Ingress Protection Rating
IQ	In-Phase and Quadrature
IRQ	Interrupt Request
ISM	Industrial, Scientific and Medical
JTAG	Joint Test Action Group
LDO	Low-Dropout Regulator
LED	Light-Emitting Diode
LNA	Low-Noise Amplifier
LoRa	Long Range Radio
LPWAN	Low Power Wide Area Network
LSE	Low-Speed External Oscillator
LTE	Long Term Evolution
MAC	Media Access Control
MCU	Microcontroller Unit

MISO	Master Input, Slave Output
MOSI	Master Output, Slave Input
NB-IoT	Narrow-Band Internet of Things
NNNco	National Narrowband Network Communications Pty Ltd
NSS	Active-Low Slave-Select
PC	Personal Computer
PCB	Printed Circuit Board
PHY	Physical Layer Protocol
PLA	Polylactide
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RFC	Radio Frequency Choke
RGB	Red Green Blue
SCK	Serial Clock
SMPS	Switched-Mode Power Supply
SoC	System-on-Chip
SPDT	Single Pole Double Throw
SPI	Serial Peripheral Interface
SSH	Secure Shell
STM	ST Microelectronics
SWD	Serial Wire Debug
TCXO	Temperature Compensated Crystal Oscillator
TX	Transmit
UART	Universal Asynchronous Receiver-Transmitter
UL	Up-Link
UNB	Ultra Narrow Band
UV	Ultraviolet
XO	Crystal Oscillator

Chapter 1

Introduction

1.1. Background and Problem Statement

Livestock farming forms a significant part of the South African agricultural sector. These farms are often very large in size, with many camps where livestock graze and rely solely on troughs as water supply. This makes it somewhat challenging for farmers to continuously monitor available water sources for livestock. It is not uncommon for farmers to arrive at camps with herds/flocks of dead animals, due to a lack of water.

In the South African context, during summer, gestated livestock can abort after 18 hours without water (W.J. de Wet, personal communication, 20 August, 2021). This has significant long-term financial implications and can be detrimental, due to the loss of future livestock.

To prevent this, farmers or farm workers drive between camps every day to check whether the water troughs are still full. This is costly in time, effort, fuel and often labour cost. In the summer, it is often needed to check the water troughs more than once a day. This is tedious, inefficient and not practical, as this also means that farmers have to be there every day. Some South African farmers drive up to 200 to 300 km per week during summer times, merely for this purpose (J. van Wyk, personal communication, 10 November, 2021).

This project aids in providing a long term, low-cost, low-maintenance and user-friendly alternative solution to this problem. It will save the farmers, farm workers and others time, money and livestock losses.

1.2. Objectives

This project serves to avoid such scenarios with the design and construction of a scalable, low-cost, smart water monitoring system, designed specifically for the South African agricultural context. A central receiver collects data from multiple water sensing devices, placed at various troughs on the farm. It sends an early warning when the water level runs low and displays a dashboard, showing the latest measurements and alerts.

The remote water monitoring system will consist of a base station and multiple field devices. The objectives to be observed for this project in order to fully address the problem as stated earlier are categorised and listed as seen below:

1 The system will work with multiple field devices and one central receiver

2 The system should work over long distances (at least 1.5 km)

3 The system should use a communication protocol independent of mobile data or cellular reception

4 The system should take water level measurements at pre-determined time intervals

5 The user should be alerted when a trough runs dry for a certain time duration

6 The field device should be powered by a solar panel

7 The design should be weather-proof

8 The field implementation should be animal-proof (livestock, especially cattle, are curious animals and will investigate a foreign object)

9 The system displays measurement results on a locally-run dashboard that:

9.1 Is understandable and interpretable by non-programmers

9.2 Is user-friendly

9.3 Will automatically update with new measurements

1.3. Summary of Work

Research was done on long range radio protocols, such as SigFox, LoRa and FSK.

The field device is designed from MCU-level, without using a development board with pre-implemented hardware and matched components. It is powered by a rechargeable battery with a solar panel and charge controller circuitry. Voltage regulation circuits ensure that the MCU (microcontroller unit) and radio receives the correct power supply. An RF sub-circuit and general functionality is implemented. Hereafter, the field device PCB (printed circuit board) is designed, as well as an enclosure and sensor mounts.

After the field device has been assembled, the MCU is programmed by JTAG/SWD (joint test action group / serial wire debug) with an ST-Link device. This software is written in C and aims to take measurements and transmit at pre-determined time intervals.

The base station is designed as a Raspberry Pi with a custom-designed HAT (hardware attached on top), which implements a LoRa transceiver. Another PCB design is conducted for the base station, and an enclosure design. The software is written to the base station using SSH (secure shell), and consists of receiver and dashboard functionality. The receiver is programmed using a combination of C and Python, whereas the dashboard, which indicates the measured results from the troughs, is programmed using Python, HTML, CSS and JavaScript. Warning messages and alerts are also sent to the user from a designated email account (troughlevelalerts@gmail.com).

Individual and specific functionality tests are performed on the field device. Finally, the entire system is tested and implemented on a farm near Swellendam, Western Cape, confirming full functional operation.

1.4. Ethical Considerations

The possible dangers that the system and device could pose to humans and/or livestock is considered as shown in the risk assessment in Table 1.1.

Table 1.1: Risk Assessment of Project

Hazard	**Probability**	**Impact**	**Risk**
Water contamination by sensor	None	None	Low
Animals get electrical shock (3.7 V)	Unlikely	Low	Low
Sharp objects on device injures livestock	None	Low	Low

It is seen that, if the project is designed correctly, it poses little to no risk to workers or animals. However, the aforementioned hazards are to be taken into account when doing all aspects of the physical design to ensure that these risks do not increase or pose any sort of danger to humans, livestock or the environment.

1.5. Scope

This report focuses on the design, functionality and operation of the water monitoring system. It does not take into account the manufacturability of the final product, although it should be reasonably simple to manufacture and implement on a larger scale.

The field device and sensor mount was designed for a rectangular, ball-valve water trough, which auto-fills itself, not taking into account other trough shapes which may require a slightly modified sensor mount.

The field device antennas selected are omnidirectional. Since the location of the farm house, where the base station will be located is known, relative to the trough, a directional antenna can be implemented and positioned towards the house, to increase the range. However, it may prove to be challenging, due to the relatively low frequency of transmission, which will result in a large required antenna size.

Furthermore, to increase power efficiency of the field device, an uplink and downlink functionality can be added between the field device and base station, ensuring that all transmitted messages are received. Bi-directional communication functionality between the field device and base station also holds the possibility for many additional functionalities which can be added, should it be desired to do so.

The sensor mount is designed for a certain depth, which is standard for water troughs. This can easily be adapted for various other trough depths.

Although the MCU does allow for sleep mode functionality, it is not implemented, as the overall power consumption of the field device is low enough that additional power reduction functionality is not necessary.

1.6. Report Overview

- Chapter 2 investigates various communication protocols and wireless technologies which could be used for this implementation. Furthermore, different methods and sensor types for water level measurements are investigated and compared.
- Chapter 3 is the system overview, detailing the operation and functionality of the overall system and its components, as well as how they interact with each other.
- Chapter 4 explains and details the hardware design of the field device. Component selection, PCB design and physical layout, in addition to enclosure design and 3D-printed sensor mount design are elaborated on and illustrated.
- Chapter 5 illustrates and outlines the software design and development for the field device, detailing the communication parameters and logic. The primary functionality and block diagrams are discussed.
- Chapter 6 entails the hardware design and development for the base station. This includes component selection, PCB layout and housing design.

- Chapter 7 explains the software development procedure and logical flow of the receiver and dashboard that forms the base station.
- Chapter 8 describes the various tests and measurements made upon implementation of the system, describing individual functionality tests performed, in addition to the experimental set-up and final practical implementation on a farm to test overall and full functionality.
- Chapter 9 contains results obtained from the various tests performed in Chapter 8.
- Chapter 10 is the conclusion, containing an overview of what was achieved in the report, objectives and metrics met, and an overall solution analysis. Furthermore, limitations of study are discussed and evaluated. Finally, the system as a whole and as prototype is assessed objectively, naming improvements and recommendations, should this work be taken further, progressed from the prototyping phase, or be implemented on a larger scale.

Chapter 2

Literature Review

2.1. Introduction

To gain better insight into the problem, in addition to various possible solutions, research is done on prospective communication protocols to be used, considering the significant portion of this project that it influences. Furthermore, different methods and types of water measuring sensors are considered and compared to decide on the most suitable way of measuring trough water levels.

2.2. Related Methods and Techniques

2.2.1. Communication Protocols

Narrow-Band IoT (NB-IoT)

NB-IoT is a derivation of the LTE (long term evolution) standard, and is designed for constrained IoT applications, using a bandwidth of 125 kHz. This narrow bandwidth reduces the data rate, and FOTA updates are hard to perform using NB-IoT. [1]

The energy and power consumption of NB-IoT is, however, very low and it has a large range in comparison with similar LTE solutions and protocols.

A drawback of using NB-IoT in a South African agricultural context is that its use requires a physical upgrade of existing LTE infrastructures, whereas many large parts of South Africa do not even have existing mobile reception, much less LTE infrastructure.

Extended Coverage GSM IoT (EC-GSM-IoT)

EC-GSM-IoT is based on eGPRS technology, opposed to LTE. Compared to other protocols in the GSM spectrum, EC-GSM-IoT brings improvements on the range and power efficiency. However, no operational EC-GSM-IoT networks are available to use to date [1].

5G

5G is one of the most recent innovations in mobile network technologies, holding many possibilities for revolutionary changes in the mobile industry, as well as IoT solutions. Currently, there are no solutions available on integrating the high-speed 5G technology with low-power solutions as required.

Furthermore, 5G reception is not freely and widely available in South Africa, meaning that it would be unrealistic to select as communication protocol for this project.

ISM Band-Based Technologies

ISM-based LPWAN technologies use unlicensed segments of the frequency spectrum, and can be used without authorisation. There are, however legal restrictions to be followed such as the duty cycle [1].

The South African ISM bands are 433.05 to 434.79 MHz and 902 to 928 MHz [2].

Sigfox

Sigfox, also referred to as "0G", is an end-to-end IoT solution, and has base stations deployed globally, provided an alternative network operator. Sigfox makes use of BPSK modulation, using a UNB carrier of the sub-GHz ISM bands.

The trade-off to this exceptionally narrow bandwidth is a slow data rate. Additionally, due to the legal restrictions imposed on the ISM band as discussed previously, up-link communications are limited to 140 per device per day, with limited size (12 bytes) [1].

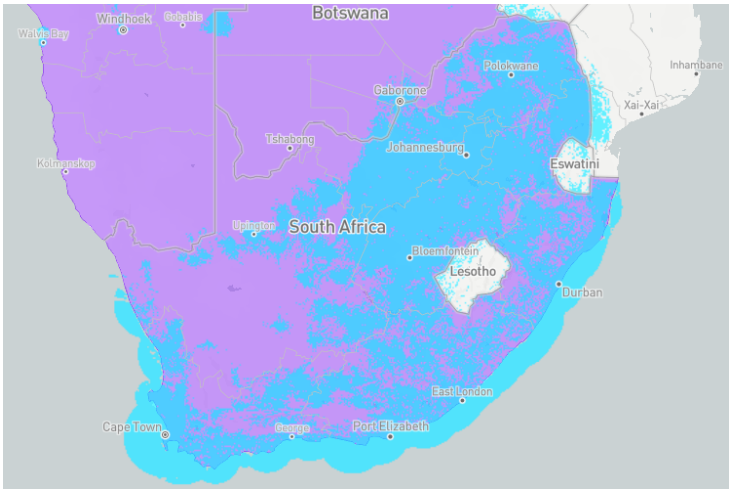


Figure 2.1: Sigfox Coverage Map - Southern Africa - September 2021 [3]. Blue indicates live coverage, whereas purple denotes areas currently under roll-out

As seen in Figure 2.1 Sigfox coverage is not available in all parts of South Africa to date. With large parts of the Karoo and Northern Cape not covered, the use of Sigfox would eliminate a significant portion of the South African agricultural sector from the group of potential beneficiaries and users.

Long Range Radio (LoRa)

LoRa is a trademarked technology, based on CSS modulation. Different bands of the ISM spectrum can be used, based on location. The South African legal bands are 433 MHz and 868 MHz [2]. LoRa communication has resilience to jamming and is exempt from Doppler deviation. It also has many parameters that can be set to adjust the range and data rate trade-off for each application's needs. The term 'LoRa' refers to the physical layer technology. LoRaWAN is a low-power wide area (LPWA) networking protocol, supported by the LoRa Alliance, which is an open, non-profit association. LoRaWAN is an open protocol for the network and MAC layers, as opposed to LoRa, which makes use of the physical layer technology only. LoRa has proven to achieve a good range when communications are in line-of-sight, but in urban settings, this range is reduced significantly. For this project's application, this would not prove to be an issue, as there will be minimal interference and the devices should be in line-of-sight with the base station.

A LoRa point-to-point communication system can be designed, or the LoRaWAN network can be extended by adding a personal gateway to the LoRaWAN network, which is publicly and freely available to use by other applications and devices in its range. [4]

Summary of Communication Protocols

A summary of the different communication protocols considered and their respective parameters are displayed in Table 2.1:

Table 2.1: Overview of Communication Protocols Considered. Adapted from [1]

Protocol	NB-IoT	EC-GSM-IoT	Sigfox	LoRa	LoRaWAN
Modulation	QPSK	GMSK	UNB DPBSK, GFSK	CSS	CSS
Band	Licensed 700-900 MHz	Licensed 800-900 MHz	Sub-GHz ISM 868 MHz (RSA)	Sub-GHz ISM 433 MHz / 868 MHz (RSA)	Sub-GHz ISM 433 MHz / 868 MHz (RSA)
Data Rate	UL 158kbps DL 106kbps	70-240kbps	UL 100bps DL 600bps	37.5mbps	50kbps
Range	15km	15km	50km (rural)	15km (rural)	15km (rural)
Payload Size	UL 125B DL 8B	Unknown	UL 12B DL 8B	up to 255B	up to 250B
Propriety	Full Stack	Full Stack	PHY & MAC Layers	PHY Layer	PHY Layer
Roll Out	Operator	Operator	Operator	Private	Operator
Full RSA Coverage	No	No	No	Yes	No

Various ISM communication protocols are considered, as discussed in Section 2.2.1. The final two options are SigFox and LoRa. Because Sigfox is provider-based whereas a LoRa network can be created privately, and Sigfox is not available in large parts of the country with many farms, as seen in Figure 2.1, it is decided to use point-to-point LoRa communications between the base station and various field devices.

The available ISM bands for LoRa in South Africa are 868 MHz and 433 MHz [5]. Taking into consideration the nature and application of this project, it is decided that a point-to-point LoRa communication system would be used, as opposed to connecting a gateway to the LoRa Alliance LoRaWAN network. This means that any practical implementations of this project will be run independently.

2.2.2. Water Level Sensors

Optical Level Sensors

Optical level sensors make use of an LED and photo-transistor. Depending on the water level and depth, the reflected or refracted light reaching the detector changes, and the water levels are measured by the sensor. However, cloudiness of water can affect measurements, which makes this sensor type not the ideal choice for this project.

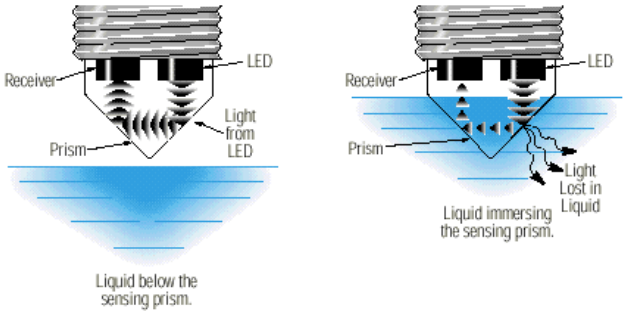


Figure 2.2: Operation of Optical Level Sensor. [6]

Capacitance

These sensors measure the change in capacitance as two plates move closer or further apart from each other, based on the water level. This type of sensor needs to be calibrated. [7]

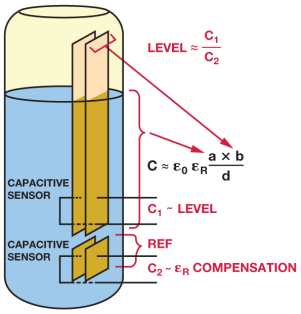


Figure 2.3: Operation of Capacitive Water Sensor. [8]

Reed Switch

A magnetic reed switch sensor contains one part fixed in place, with another piece floating on the water surface, rising and falling along with the water levels. When the float reaches a certain point, the magnet closes and completes a circuit. This type of sensor is reliable in the long term and is the most cost efficient. However, exact levels are not measured and it is only known whether the water level is above or below a certain calibrated threshold.

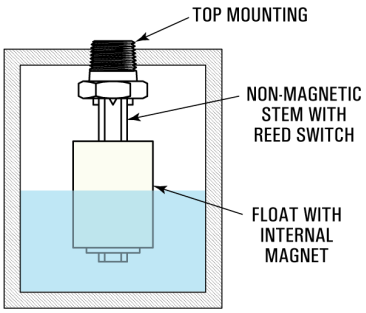


Figure 2.4: Operation of Reed Switch Sensor. [9]

Conclusion

After consideration of the above-mentioned types of sensors, it is decided to use a reed switch sensor, due to its low cost, simple implementation, easy calibration and reliability. Furthermore, the water troughs which this project is based on has a full water level of 30 cm, and the only point of interest is when the level is below a certain threshold. It is not relevant or important to know the exact trough water level, given that it is not empty (W.J. de Wet, personal communication, 20 August, 2021).

2.3. Existing Commercial Applications

2.3.1. Incyt by LX

Incyt uses a float based sensor to measure water troughs, and is based in Australia [10].

Objectives

- Protect livestock from dehydration by measuring water in troughs
- Alerts user when there is no water in the trough
- Data visualisation is provided by a dashboard

Method

Incyt uses the LoRaWAN network and NNNco LoRaWAN connectivity as protocol. The sensor floats on the water surface in the trough and has an internal mechanical ball and micro-switch combination, measuring the water level. The sensor casings are made from IP69-rated material.

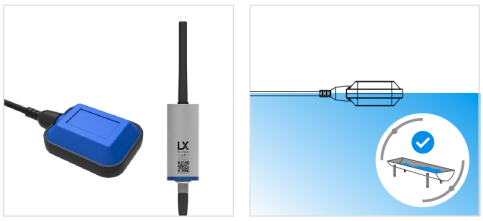


Figure 2.5: Incyt Trough Level Sensor Application [10]

Results

Incyt has a commercial implementation in Australia and is currently quoting, selling and distributing across the country.

Remaining Challenges

- The device is not protected from livestock, and floats openly on the water surface
- The device battery is not rechargeable and needs to be replaced
- The dashboard does not alert the user of an empty trough other than the dashboard display
- The system is dependent on the assumption of an available gateway, which would not be the case in a South African application
- There is no calibration option or measuring threshold to classify the trough as being empty

2.3.2. FarmBot Monitoring Solutions

Objectives

- Forewarns user of impending problems
- Wireless transmission
- Sensor cable guard and base plate add-on

Method

The Farmbot monitoring solution makes use of satellite and cellular networks for communication. The system requires a Farmbot Monitor as base station.

Figure 2.6: Farmbot Monitoring Solutions Application [11]

Results

The system works for a range of 2 to 5 km between the trough and Farmbot Monitor. The field device has a battery life of 1.5 to 2 years, and has a water measurement range of up to 125 cm.

Remaining Challenges

- Communication is dependent on a cellular network and it is therefore not suitable for South African application
- The system requires a Farmbot Monitor device to work and cannot be integrated with other systems

2.3.3. Conclusion

The existence of commercially available solutions across the world validates and legitimatises the problem as described in Section 1.1 and need of a solution such as this project. This proves the need of a working, reliable and practically realisable solution in a South African context.

Chapter 3

System Overview

3.1. Functional Block Diagram

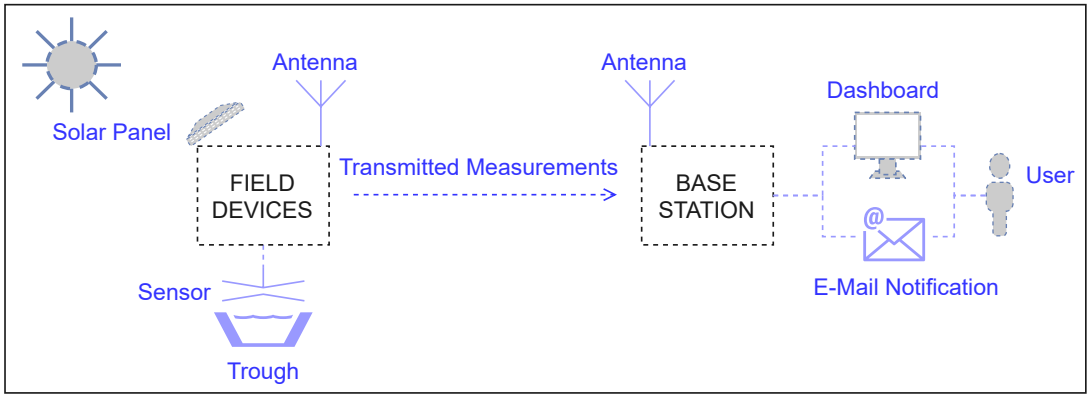


Figure 3.1: System Diagram

Displayed in Figure 3.1, the water monitoring system consists of multiple field devices communicating with a central base station. Field devices are mounted on poles near respective water troughs (one device per trough). It is powered using a solar panel and is connected to a sensor which lies in the trough. Measurements are taken every six hours and an antenna transmits results to the central base station. The base station receives transmitted packets from the respective field devices and graphically displays measurements from the last 48 hours, colour-coding results for an easy overview. When an alert condition is experienced by one or more troughs, an email is sent to an address set by the user, and the dashboard displays an alarm condition and indicates this to the user. The full dashboard functionality, as well as what is considered an alarm condition, can be found in Chapter 7.

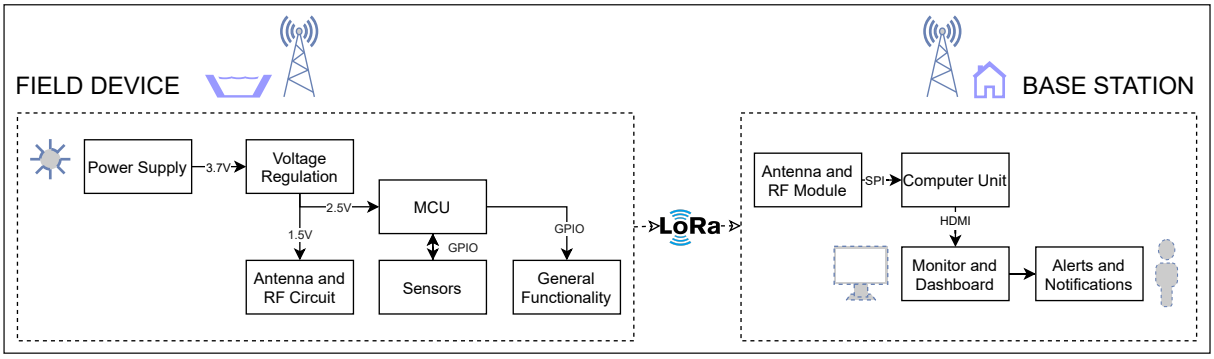


Figure 3.2: Functional Block Diagram for System

The functional block diagram of the entire system is seen in Figure 3.2. The field device has sub-circuitry for power supply, voltage regulation, the micro controller, RF circuitry, sensors and other general functionality. It communicates using LoRa to the base station,

which consists of an antenna and RF module, computer unit and a monitor. Communications will be at 868 MHz, as the higher frequency simplifies PCB design due to narrower tracks being required to optimise the rf communication. This PCB design is discussed in Section 4.2.

3.2. Field Device

The functional block diagram of a field device is displayed in Figure 3.3. A custom designed enclosure is 3D-printed as discussed in Section 4.3. A custom PCB and device is designed and used, as opposed to the use of a pre-existing solution like a development board, for an enhanced customisation of the device.

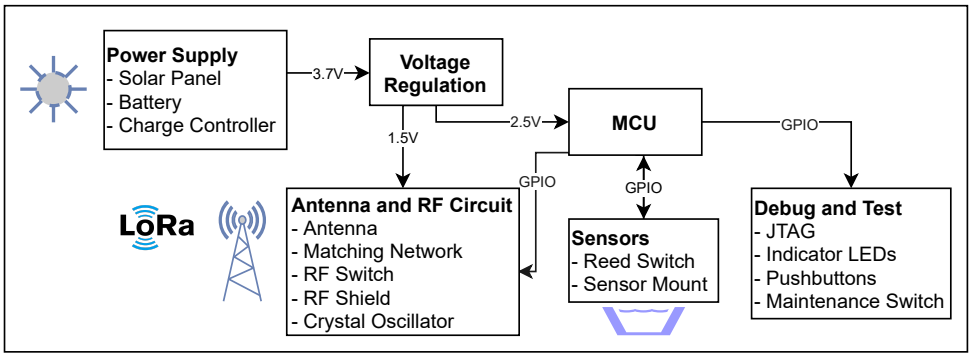


Figure 3.3: Field Device Functional Block Diagram

3.3. Base Station

The functional block diagram of the base station is shown in Figure 3.4. It consists of a Raspberry Pi, custom HAT with a LoRa-module and antenna. A PCB is designed for the HAT as explained in Section 6.2. The computer unit reads data received by the LoRa module, processes it and runs the dashboard and notification protocols. For this, Raspberry Pi and Arduino are considered as possible solutions. Due to time constraints, and given the complexity of the field device design, it is found suitable to use an existing computer solution for the base station. Access to a Raspberry Pi and budget constraints led to the decision of using a Raspberry Pi 3 Model B+ as computer unit for this device, which will have the custom HAT mounted on top. This computer unit can run on any monitor or display with an HDMI port and runs independently from other PCs. This monitor is placed in the farmer's house and forms an integral component of the base station.

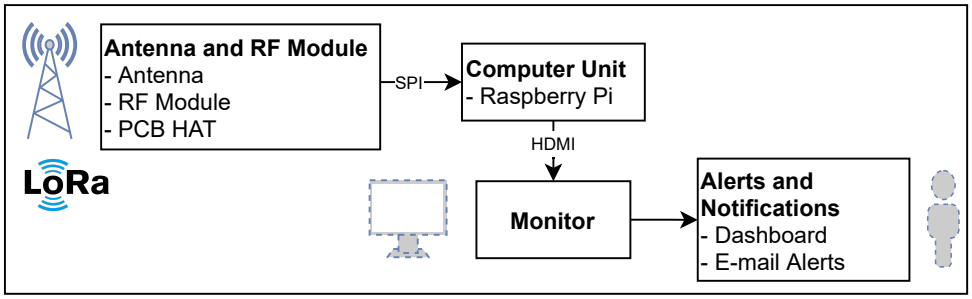


Figure 3.4: Base Station Functional Block Diagram

Chapter 4

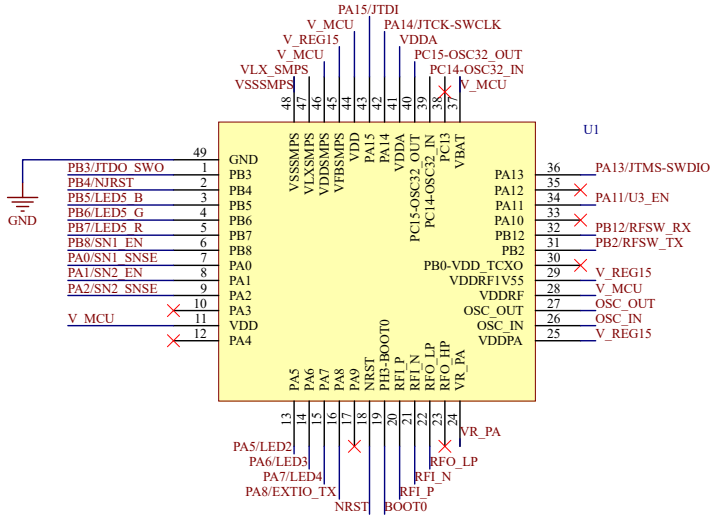
Field Device: Hardware Design

4.1. Schematic and Circuit Design

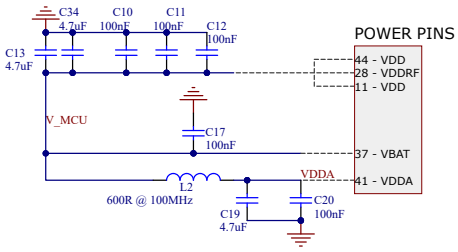
The full schematic for the field device can be found in Appendix C. A detailed breakdown of the circuitry design and component selection for the field device follows.

4.1.1. Microcontroller

The microcontroller (MCU) controls the functions of the entire device, and will be programmed to operate with the exact functionality that this device is designed for. An MCU is selected from the ST Microelectronics STM32WL series, which claims to be the world's first LoRa-enabled SoC [12]. Existing solutions or pre-configured LoRa modules were looked into, such as those from Adafruit Industries, Arduino or Semtech. However, it was decided to design from MCU-level, ensuring an advanced understanding of all functionality and making the overall solution more compact. This enhanced customisation adds to effective operation without any unnecessary peripherals or unused functionality, adding to effective power consumption.



(a) MCU



(b) MCU Power pins

Figure 4.1: Schematic for MCU and Power Pins

MCU

The MCU pins are configured as seen in Figure 4.1a, for the required functionalities from software-controlled elements and components, including GPIO, RF circuitry and control pins.

Power Pins

Each power supply pair (eg. `VDD/VSS` or `VDDA/VSS`) is decoupled with a 4.7 μF capacitor, and there is a 100 nF capacitor for each power pin in use on the MCU [13]. The

100 nF capacitors `C10, C11, C12, C17` and `C20` decouples MCU pins 44, 28, 11, 37 and 41, respectively. This is indicated on Figure 4.1b. The power pairs decoupled by 4.7 μF capacitors are VDD, VDDRF and VDDA, by `C13, C34` and `C19`, respectively. The decoupling of the SMPS power supply pair follows the same rules and is shown in Section 4.1.2.

A ferrite bead is used as choke between nets VDDA and VDD to prevent current flow among the pins, which could damage the radio and MCU. A component with high resistance at frequency fluctuations below f_{op} is selected (600 Ω@100 MHz). This is shown in Figure 4.2. It should be noted that at the operating frequency (868 MHz), the resistance is significantly lower, and device operation is therefore not impacted.

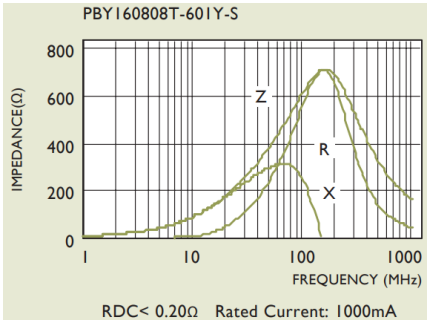
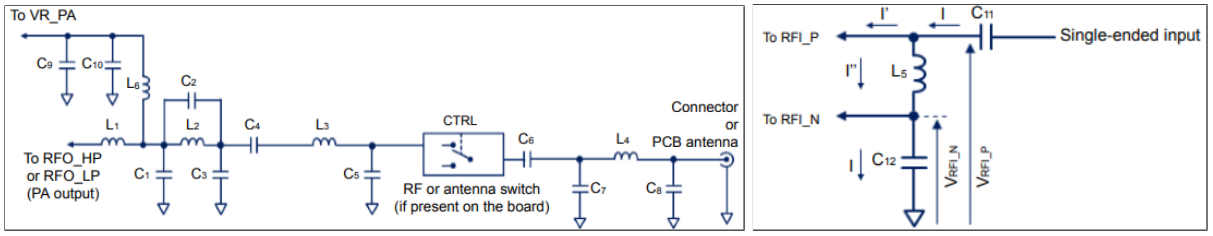


Figure 4.2: Frequency Response Electrical Characteristics of `L2` [14]

4.1.2. RF Design

As discussed in Section 2.2.1, LoRa at 868 MHz is selected for communications. An 868 MHz omnidirectional RF antenna is used, and the RF matching network is designed. An SPDT RF switch is controlled by the MCU using General-Purpose Input/Output (GPIO), configuring transmit or receive mode. An RF shield is placed over the MCU, matching network, crystal and oscillator, minimising external RF interference and self-interference from the antenna.

The design seen in Figure 4.4 was supplemented by a typical application network as seen in Figures 4.3a and 4.3b, from the STM web page [15].



(a) TX Network **(b)** RX Network

Figure 4.3: RF Design Guide Typical Networks [15]

The RF circuit is designed for the following parameters:

- $f_{op} = 868$ MHz
- Antenna Impedance: 50 Ω
- Transmit Power: 14 dBm

The transmit power is the highest possible strength of transmission under low-power operation mode of the MCU. The following subsection explains the design decisions and parameters made in reference to Figure 4.4.

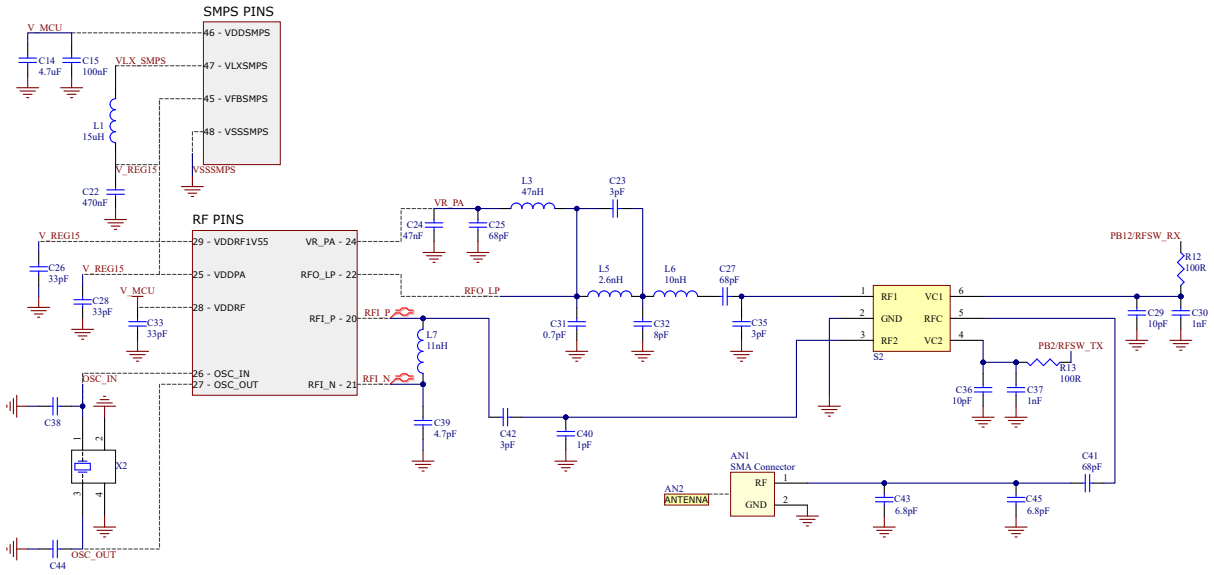


Figure 4.4: Designed RF Circuit Schematic

Nets

The pins `RFI_P` (pin 20) and `RFI_N` (pin 21) are used as a differential pair for receiver functionality, per the MCU data sheet [13]. They are designed as 100 Ω nets in parallel, resulting in an effective impedance of 50 Ω. This is matched throughout, from the MCU to the antenna for optimal rf results. The transmit pins on the MCU are `RFO_HP` (pin 23) and `RFO_LP` (pin 22). Only `RFO_LP` is used, leaving `RFO_HP` unconnected.

The MCU's internal power amplifier (PA) outputs the voltage supply `VR_PA` to the RF circuit. This power amplifier is supplied from the external regulated 1.5 V supply to `VDDPA`, also seen as `V_REG15` on Figure 4.14. In low-power transmit mode, `VDDPA` is connected to the 1.5 V regulated supply, via the SMPS feedback pin, `VFBSMPS`.

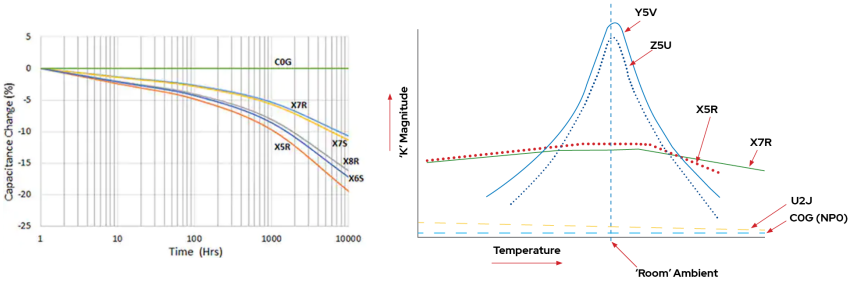
Component Selection

Using Eq. (4.1) to (4.3) to calculate the impedance of inductors, capacitors and resistors, respectively, all nets are aimed to be matched to 50 Ω. The fully designed parameters of each component can be found in Appendix G. The components are selected based on these properties but, to limit content, every component parameter is not explicitly elaborated on in this section.

$$Z = j\omega L \tag{4.1}$$

$$Z = -\frac{1}{j\omega C} \tag{4.2}$$

$$Z = R \tag{4.3}$$



(a) Ageing Characteristics [16] **(b)** Decay with Ambient Temperature [17]

Figure 4.5: Capacitance Decay for Different Dielectrics

Where possible, C0G/NP0 is the preferred dielectric for capacitors, due to their reliability and integrity with varying temperature, voltage and time. From Figure 4.5, it is clearly the most stable and reliable dielectric. However, since the deviation from standard capacitance values within the operating conditions of this device is relatively small, X7R and X5R are selected when C0G/NP0 components are unavailable. Ceramic capacitors are preferred for all RF components for their high stability and low losses with varying applied voltage, temperature and frequency [18]. This also means that extremely low tolerances are possible, which is important for this design.

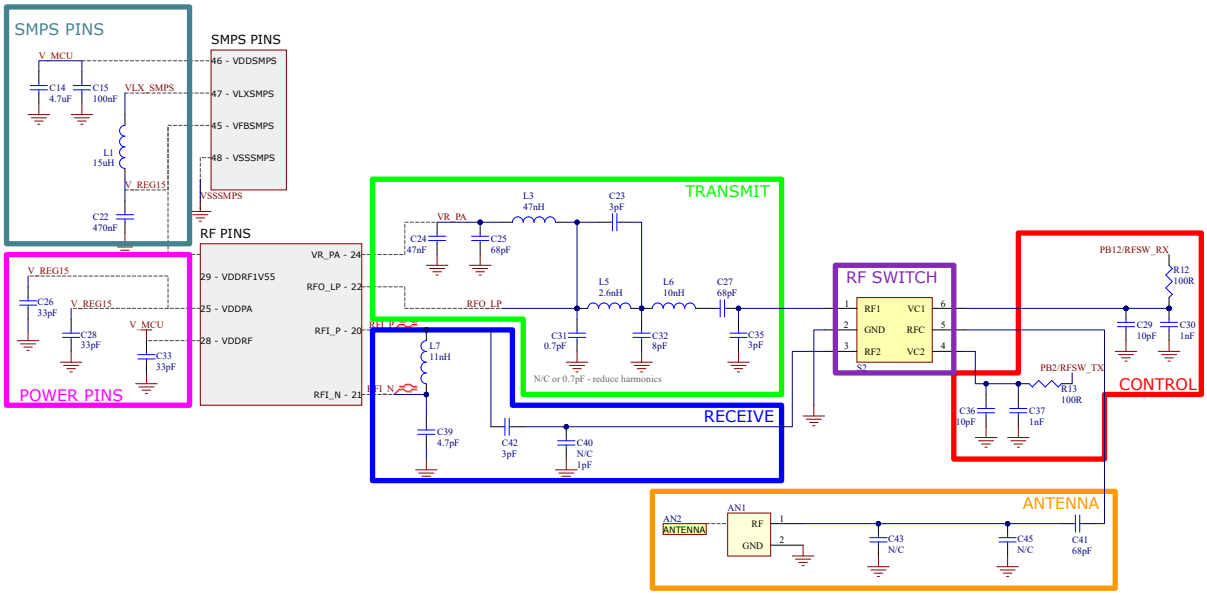


Figure 4.6: Segmented RF circuit

When available, 0402 size capacitors and inductors are used, as they are known for lower inductance than larger sizes. [19]. This reduces the deviation from theoretical calculations, resulting in enhanced reliability and true-to-design results. The RF circuit design is explained in sub-sections, seen in Figure 4.4.

SMPS Pins

The SMPS pins from the MCU are configured using design guidelines from the MCU data sheet [13]. The MCU power amplifier can be configured in either LDO mode or SMPS mode when using the low-power transmit functionality of the radio. It is decided to use the SMPS mode due to the higher power efficiency rate than LDO's typically provide [20]. `L1` is selected as 15 μH and acts as an SMPS choke. A shielded inductor is used, to minimise noise.

Power Pins

33 pF bypass capacitors are implemented for all 1.5 V powered pins, such as VDDPA (pin 25), VDDRF1V5 (pin 29), and VDDRF (pin 28), bypassed by `C28`, `C26` and `C33`, respectively. Due to the narrow bandwidth used, a single bypass capacitor per pin is sufficient.

Transmit

VR_PA Filtering and Biasing

`C24` is a bulk capacitor and mitigates the voltage drop from the VR_PA supply when power is not available. It therefore also protects other components from voltage fluctuations. A value of 47 nF is chosen, per typical value given by an RF design guide [15].

The inductor L3 is an RF choke (RFC) to block AC current and is selected as 47 nH, the recommended value for an operating frequency above 800 MHz [15]. Its equivalent impedance at the operating frequency is 256 Ω, calculated using Eq. (4.1). Higher frequencies will be blocked by the choke. A wire-wound inductor with a magnetic core is desired and selected [21], with a resonant frequency of 2.9 GHz $\approxeq 5 \times f_{op}$, eliminating high frequency noise typically found in a present-day environment.

C25 is selected as 68 pF, the typical value for this application [15]. Using Eq. (4.4), which calculates the resonant frequency of an LC series filter, C24 and C25 result in a low-pass filter with a resonant frequency of 890 MHz $\approxeq$ $f_{op} = 868$ MHz, resulting in the desired filter characteristics at low frequencies.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{4.4}$$

Band-Stop Filter

C23 and L5 form a parallel resonant band-stop filter, filtering out the second harmonic. It has a high impedance at its resonant frequency, 1.8 GHz, calculated using Eq. (4.4).

C-L-C π-filter

C32, L6 and C35 form a C-L-C π-filter. A band-pass filter is created by combining this with L5 and C31. This results in a low-pass response. Additionally, C31 assists in reducing harmonics.

DC-Blocking Capacitor

C27 acts as DC-blocking capacitor and is given the standard value recommended by RF design guidelines for this MCU [15].

Receive

The receive network is focused mainly on the phase shift between the differential pair.

L7 lies in series between the two phases RFI_N and RFI_P, resonating with C42 at 876 MHz, using Eq. (4.4), where $L7 = 11$ nH and $C42 = 3$ pF. The differential pair will therefore operate as desired at $f_{op} = 868$ MHz.

The combination of C42 and C40 is approximately equal to $C39 = 4.7$ pF. This results in complimentary phases between the differential pair nets. The capacitor divider formed by C42 and C40 from the antenna may cause an imbalance and deviation from the perfect differential pair phase shift required. This is countered by selecting C39 with some ESR, trading it off with insertion loss. For optimal RF results, size 0402 (imperial) capacitors are used, and the ESR plot of C39 is seen in Figure 4.7. It is noted that the ESR at f_{op} will be approximately 60 mΩ. C40 acts as a capacitive divider and is selected as 1 pF. C41 gives a single-pole high-pass response and acts as a coupling capacitor.

RF Switch

The RF switch alternates, connecting the antenna with either the transmit or receive sub-circuit. A switch with two control pins is selected. These pins are powered by MCU GPIO 2.5 V, which lies in the switch control logical high voltage range (1.8 to 5.3 V). Therefore, the pins can be controlled by the MCU. The operating frequency range of the RF switch (50 MHz to 3000 MHz) is suitable for the operating frequency $f_{op} = 868$ MHz. Its input power is rated at 33 dBm, well above the transmit power of this device (14 dBm).

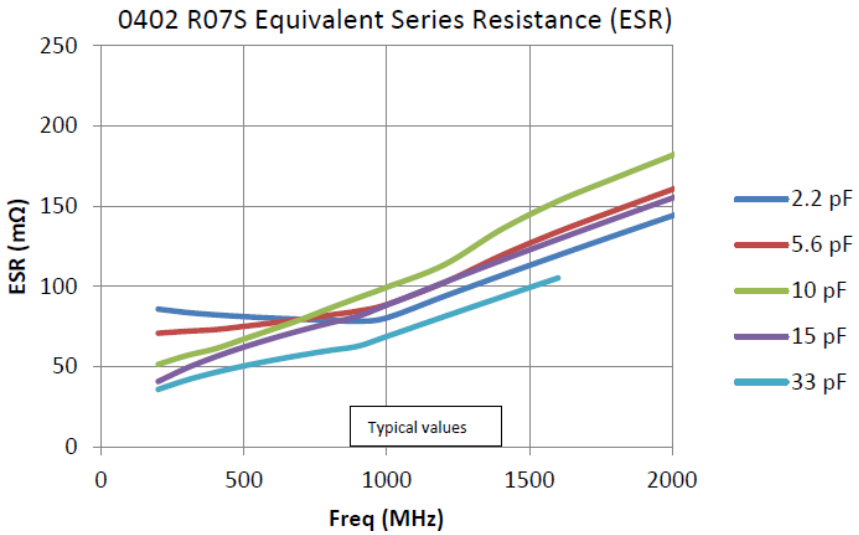


Figure 4.7: ESR plot of `C39` [22]

Control

The MCU uses GPIO to control the RF switch. The control sub-circuit regulates these voltage fluctuations, protecting the RF switch and the MCU from damage while maintaining reliability of operation and component integrity.

A 10 pF and 1 nF decoupling capacitor is added to each control pin to suppress transients that occur from switching. This stabilises the circuit and makes the response more reliable. A current-limiting 100 Ω resistor is added.

Antenna

A 50 Ω, 868 MHz antenna with 2 dBi gain and linear polarisation is selected. This reduces the matching efforts to be made significantly. A DC-blocking, 68 pF capacitor, `C41`, is placed at the RF switch port. Two 6.8 pF decoupling capacitors, `C43` and `C45`, are placed to filter out high-frequency external signals such as Wi-Fi (2.4 GHz).

4.1.3. Crystals and Oscillators

External oscillators are implemented as seen in Figure 4.8. `X1` is the LSE and `X2` is the HSE.

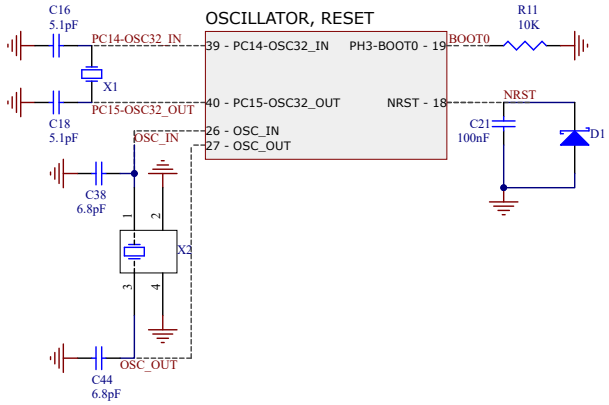


Figure 4.8: Schematic for External Oscillators

High-Speed External Oscillator (HSE)

Per MCU data sheet design recommendations, a 32 MHz HSE oscillator is selected. This improves time-keeping accuracy of the device when in sleep or low-power mode, and acts as back-up if the MCU's internal oscillator fails. A 6.8 pF decoupling capacitor is installed close to each pin of the oscillator. Two of the component pins are connected to GND, providing mechanical stability to the component.

Low-Speed External Oscillator (LSE)

A 32.368 kHz LSE is implemented, following guidelines from the MCU data sheet [13]. It is connected between MCU pins `PC14` and `PC15`. The LSE does timekeeping while the field device is in low-power mode.

4.1.4. Sensors

Two reed switch sensors are used to measure three distinct water levels. Each sensor has two wires. One end is configured as GPIO input (`SNSE`) and the other is configured as GPIO output (`EN`). Extension wires `W1 - W4` are connected between the field device and sensors, described in Section 4.2.

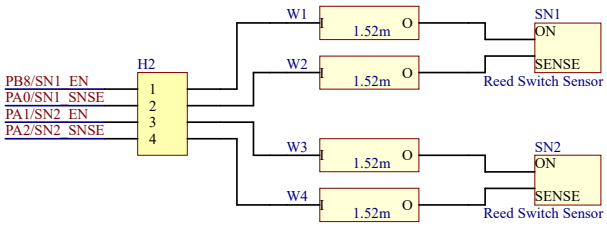
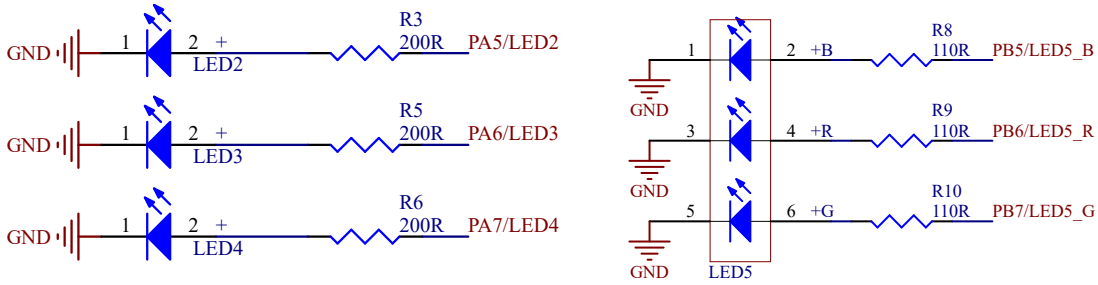


Figure 4.9: Schematic for Sensor Wiring

4.1.5. General Functionality

For further debugging purposes, prototyping and user interaction, LEDs and push-buttons are implemented. Three green LEDs, `LED2, LED3` and `LED4` are used for level indication and represent the three water levels that can be measured. An RGB led, `LED5`, is used as status-indicator.



(a) Level Indicator LEDs **(b)** Status LED

Figure 4.10: Schematic for LEDs

Level Indicator LEDs

Taking into consideration the overall device power consumption, an LED with a low current draw is selected. The LEDs are powered by `PB5, PB6` and `PB7`, respectively. As the GPIO pins output 2.5 V, the current is limited to 12.5 mA with a 200 Ω resistor in series with each LED to GND. The absolute maximum rated current according to the

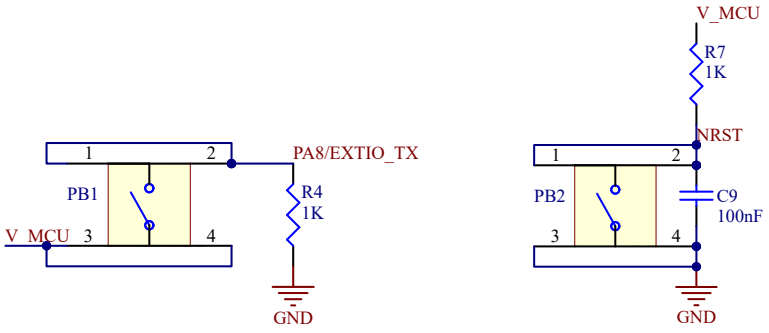
LED data sheet [23] is 25 mA. The LED therefore operates at half its rated current. The circuit configuration is shown in Figure 4.10a.

Status LED

The RGB LED is a single component, operated using three embedded sub-circuits independently, as shown in Figure 4.10b. It is controlled by `PA5`, `PA6` and `PA7`, respectively. The absolute maximum forward current rating of the Red, Green and Blue LEDs are 50 mA, 30 mA and 35 mA, respectively. The circuit is designed for 22 mA, and three current-limiting resistors of 110 Ω are placed in series to GND.

Push-Buttons

Two push-buttons are implemented. The first push-button is used to reset the device (`RST`), and the second is a transmit button (`TX`). Common tactile switches with slightly longer actuators are selected, making it easier to press. The push-button implementations are displayed in Figure 4.11.



(a) Transmit Button **(b)** Reset Button

Figure 4.11: Schematic for Pushbuttons

TX Button

The TX button has an external pull-down 1 kΩ resistor as seen in Figure 4.11a. When the button is pressed, the MCU pin is connected to `V_MCU` (2.5 V), driving it high and triggering an external interrupt in software (refer to Chapter 5).

RST Button

The MCU has an active-low reset pin, pulled up with a 1 kΩ resistor to avoid false resets. Like the other power pins of the MCU, it is decoupled with a 100 nF capacitor to GND. This is reflected in the schematic seen in Figure 4.11b.

4.1.6. JTAG and Debugging

SWD and JTAG are considered for programming and debugging purposes. SWD is intended for micro-debugging, whereas JTAG is designed largely for chip and board testing, which is more relevant for this project. Therefore, JTAG is used for software development and implementation on the custom board and MCU. An ST-Link/V2 is used to program the MCU, using 5-pin JTAG with a 20-pin ribbon, per the debugger data sheet [24]. More information regarding the debugging of the MCU and software development is found in Chapter 5.

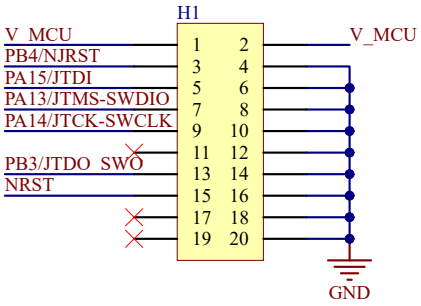


Figure 4.12: Schematic for JTAG

4.1.7. Power Supply

The power supply schematic is shown in Figure 4.13.

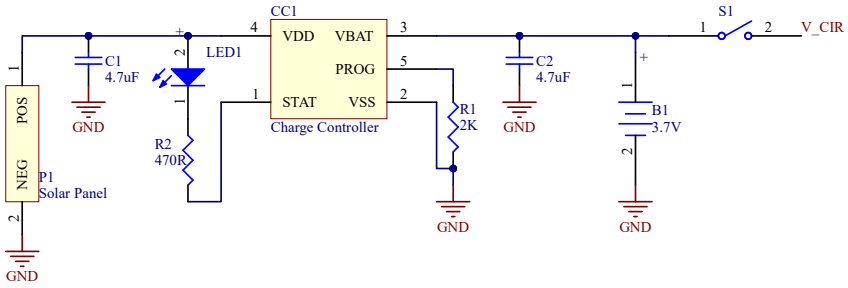


Figure 4.13: Schematic for Power Supply

Power Calculations

Before the power supply is designed, the total power and current consumed by the field device under typical operating conditions is calculated as seen in Table 4.1.

Table 4.1: Power Calculations

	Component		Current mA	Voltage V	Power mW	Power mWh
U1	MCU: Running (SMPS Active) (Always running)	[13]	3.45	2.5	8.625	8.625
U1	MCU: TX, 868MHz, 14dBm (1 minute every 6 hours)	[13]	26	1.5	39	0.108
U2	2.5V Regulator (Always running)	[25]	1.8	3.7	6.66	6.66
U3	1.5V Regulator (65 seconds, every 6 hours)	[26]	0.85	3.7	3.145	0.0094
LED2-4	3×Green LEDs (Level Indicator) (3×1 second every 6 hours)	[23]	12.5	2.5	31.25	0.0015
LED5	RGB LED (Status) (30 seconds every 6 hours)	[27]	22	2.5	55	0.0715

Solar Panel

A rechargeable battery is used as power supply. Since the field device will be placed outdoors, it is sensible to have it solar-powered, rather than having the user manually charge batteries for all troughs regularly. Due to the small physical size of the field device, the smallest possible solar panel with a sufficient power rating is selected.

From Table 4.1, the total average power consumption is 15.475 mWh, amounting to 371.4 mW per day. Assuming a worst-case scenario of four hours of full solar exposure per day, it is calculated that a solar panel with a power rating of at least 92.85 mW is needed. The power supply schematic is shown in Figure 4.13. A 0.5 W solar panel is chosen, based on the power consumption calculations previously shown. It is selected for its small physical size, sufficient power rating and low cost.

Charge Controller

A charge controller is selected to regulate the power supply from the solar panel to the battery. An LED indicates that the charging circuitry is active. The capacitors and resistors are chosen from the charge controller data sheet [28].

Battery

The voltages required for operation will be 2.5 V for the MCU and 1.5 V for the radio circuitry. A 3.7 V, 2600 mA h, 18650 rechargeable battery is selected. From Table 4.1, it is calculated that the battery should last 26 days from a single recharge.

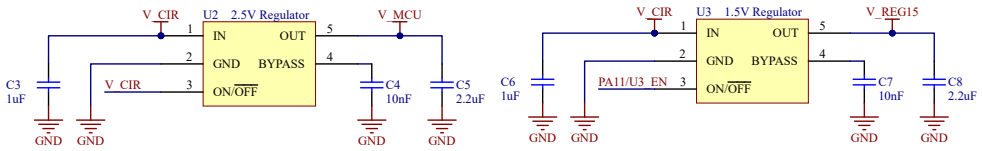
DIP Switch

A DIP-switch is placed between the battery charging circuitry and the rest of the circuitry. This ensures that, even when the field device is not switched on or in use, the solar panel can still charge the battery. It is switched off when the device is not in use or when maintenance is performed, protecting the circuitry.

4.1.8. Voltage Regulation

From the desired power supply to the micro controller and radio, two voltage regulators are selected to step the battery supply down to 1.5 V and 2.5 V, respectively. The battery supply voltage lies in the input range of both regulators.

For simplicity, both regulators were chosen as SOT23-5 packages. This size is small enough to ensure a compact device design, but still large enough to be soldered easily. The schematics are shown in Figure 4.14.



(a) 2.5 V Regulator **(b)** 1.5 V Regulator

Figure 4.14: Schematic for Voltage Regulation

2.5 V Regulator

The battery supply is adapted using a voltage regulator `U2`, to supply the MCU with a regulated voltage of 2.5 V, with the implementation shown in Figure 4.14a. As the MCU always has to be powered when the power supply is on, the `EN` pin is pulled up to `V_CIR` (battery supply). The capacitors are selected based on recommendations from the voltage regulator data sheet [25].

1.5 V Regulator

A voltage regulator `U3` is implemented to regulate the battery voltage to 1.5 V, required by the MCU RF pins and radio [13]. To limit the overall power consumption of the device, this voltage regulator is implemented with a GPIO EN pin `PA11` and will be driven high

by the MCU whenever the device is preparing to send or receive, therefore the regulator is inactive when not in use and does not consume power. The circuit configuration seen in Figure 4.14b is based on the recommended design from its data sheet [25].

4.2. PCB and Component Layout

This section describes the PCB design process of the full PCB layout as seen in Appendix D. Polygon ground pours are added to the top and bottom layer. These are connected with vias to prevent ground loops. This plane acts as a return path for many components' current. The PCB is aimed to be as small as possible to ensure large scale manufacturability and for practical reasons regarding installation and use in the field. The PCB layout is segmented as seen in Figure 4.15.

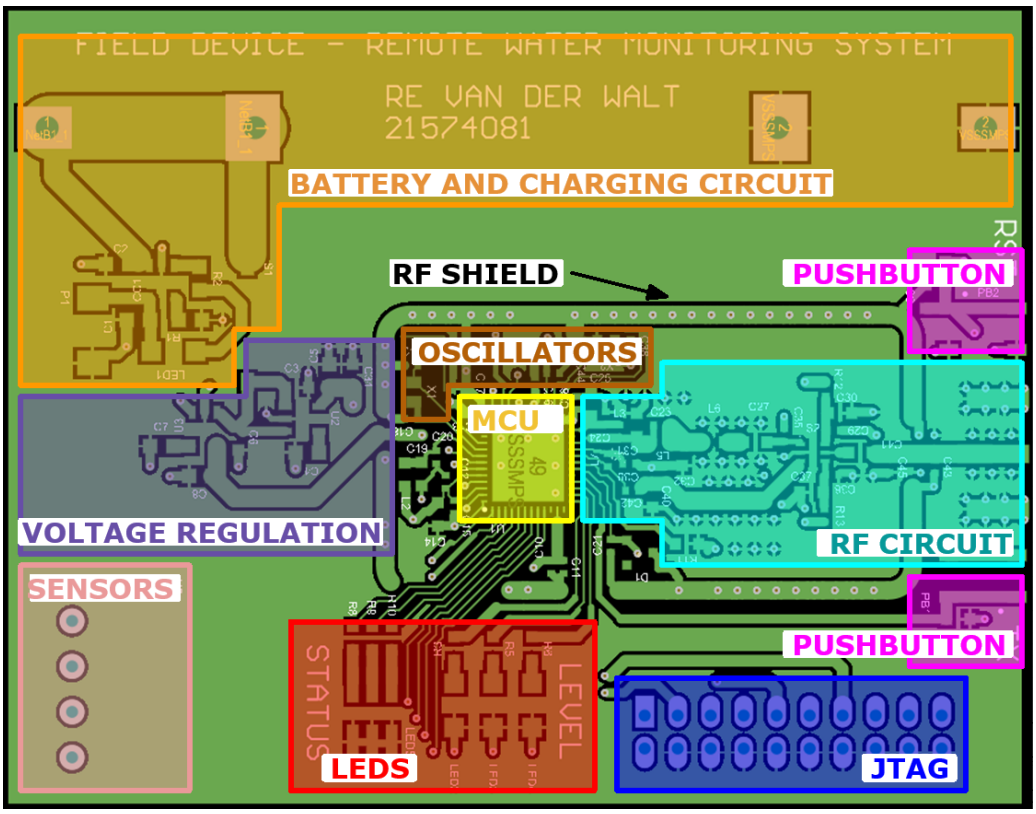


Figure 4.15: Segmented PCB Layout for Field Device: Top View

4.2.1. Layout and Placement

Battery and Charging Circuit

The battery is the largest component on this device and therefore constrains the minimum PCB length. It is placed with its positive terminal away from the RF components. The charging circuitry is placed close to the positive terminal of the battery. The solar panel connector is placed near the board edge for easy connection and detachment of the solar panel.

Voltage Regulation

The voltage regulators are naturally placed near the power supply circuit. The outputs of these components are connected to the relevant power and radio pins on the MCU.

Sensors

The four GPIO pins involved with the sensors are connected to a header on the board bottom. This ensures that all cables will enter the casing from below when mounted, entering the device from the direction of the trough.

LEDs

The LEDs are placed near the board edge, close to each other, so that the user can see through a window what state the device is in or what measurement has been made. The three level sensors are distributed vertically from one another, imitating the rising water levels, and the status LED is placed below.

JTAG

The JTAG header is mounted on the bottom of the board, purely to make the routing process and PCB design easier. This header also acts as a supplementary mount of the PCB in its casing.

Pushbuttons

The pushbuttons are placed alongside the RF circuit. As it is mostly used for debugging purposes and not intended to be used frequently, it is placed relatively far away from the other user interaction components.

MCU

The MCU is the most interconnected component on the device, and interacts with almost all other components directly or indirectly. It is therefore placed in the PCB centre, and positioned to make routing as easy as possible.

Oscillators

A thermal barrier / metal clearance is placed around the HSE to reduce thermal conduction. This is to compensate for the fact that an XO is used as opposed to a TCXO (refer to Section 10.3.1). The LSE is placed close to the MCU per data sheet recommendations [13].

RF Shield

An RF shield is placed over the RF circuit (except the SMA connector and its decoupling capacitor `C43`), MCU and oscillators. This reduces EMI and parasitic capacitance. An aluminium shield frame is soldered onto the PCB, connecting to GND, and a removable aluminium cover clips over it, so that there is still a way to access the components underneath it should debugging or maintenance be performed.

RF Circuit

A standard 0402 footprint is adapted to make the pads slightly longer, alleviating the soldering process. This is to reduce the chance of tomb-stoning (when the component is lifted up-right from the PCB) and the head-in-pillow effect, due to heat from the soldering iron damaging the component. These slightly longer pads make it easier for the soldering iron to evenly heat up the pad and component. The pads are 0.7×0.6mm, whereas the typical land pattern is 0.6×0.5mm. The most important of the many guidelines followed when approaching RF component placement are summarised as follows:

- Discontinuities on the RF track were avoided.
- The RF track was kept straight with bends and T-junctions in the RF track avoided as far as possible.

- Filter inductors and chokes such as `L1` and `L3` were placed perpendicular to LNA and RF tracks to minimise noise.
- Decoupling capacitors were placed as close as possible to the MCU and / or power pins to maintain power integrity.
- The RF path does not include any vias.
- The track length and width was calculated to match 50 Ω at 868 MHz.

After the RF components were placed, the track width was calculated using Eq. (4.5), where w is the track width in mils, Z_0 is the single-ended impedance in Ohms, h is the dielectric thickness in mils, ϵ_r represents the relative dielectric constant and t is the substrate thickness. A graphical representation of these parameters are displayed in Figure 4.16. To minimise the required track width, a 0.8 mm FR-4 substrate is used with a relative dielectric constant $\epsilon_r = 4.4$. Using Eq. (4.5), the desired track width for the RF circuitry is 1.45 mm.

$$w = \frac{7.48 \times h}{\exp(Z_0 \frac{\sqrt{\epsilon_r}+1.41}{87})} - 1.25 \times t \tag{4.5}$$

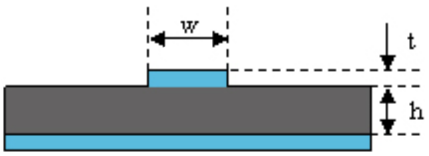


Figure 4.16: RF Track Width Calculation Parameters [30]

It should be noted from Figure 4.15 that the track from the SMA connector to the MCU is as straight as possible and does not contain any bends. Ground vias are placed tightly surrounding the signal-carrying tracks to mitigate electromagnetic interference. This helps to reflect radio waves from other antenna elements.

4.2.2. PCB Printing and Specifications

Due to the nature of this design, and the crucial roles that component size and vias play, it is decided to have the field device PCBs printed with solder resist and plated vias, rather than using the university's routing machine.

This decision was specifically made with consideration to the MCU pins' size which is 0.25 mm wide with a 0.25 mm space between pins. The MCU package is UFQFPN48 and has dimensions 7×7 mm with 48 pins, of which 40 are used in this application and therefore routed out. The routing machine's resolution would barely allow for these specifications. The thin pads would pose extreme difficulty and have a high probability of lifting and coming off the fibreglass board while soldering. The 0402 components would have also been much more difficult to solder if the routing machine was used without a solder mask.

Furthermore, due to the high number of MCU pins which requires routing out (12 pins on each 7 mm side), tracks coming from the MCU are 0.25 mm wide. This would also pose a high risk of coming off the board while soldering or handling the PCB, with the copper exposed.

Due to the many tracks in a tiny region, many vias are required to make all the necessary connections on the PCB. The minimum drill size of the routing machine is 0.8 mm, requiring the vias to be at least 1.6 mm in diameter, which is practically unrealisable given the available space. In addition to this, ground vias are placed around the antenna track to

minimise EMI and ground loops. The routing machine cannot create plated vias and, considering the number of vias on the field device PCB (168 vias per device), it is not reasonably practical to manually solder these one-by-one.

For the above reasons, it is justified to have PCBs made for the field devices to increase the chance of achieving success with the final product.

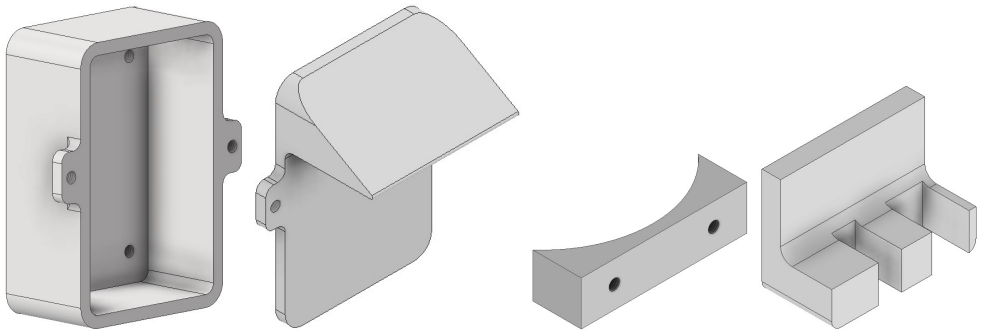
4.3. Enclosure Design

A casing is 3D-printed for customisability with black PLA, which is not UV-protected. This is suitable for prototyping purposes, but for a long term solution, an alternative material should be used. To prolong the casing and device lifetime, it is painted with UV-protective, white paint. The aim is to test the system on a farm near Swellendam (refer to Section 8 for testing and measurement details), and before the casing is designed, measurements are made of the troughs, poles and fences to ensure that the design is practically realisable and useful in a practical environment for this context. Figure 4.17 shows the troughs.

(a) 21 August 2021 **(b)** Installation Design

Figure 4.17: Trough Inspection and Measurements prior to Design

The field device will be mounted near the top of a 1400 mm long pole (seen as A on Figure 4.17b), to limit livestock interference and access. Extension wires will run down to B and the sensors will lie inside the trough. There is already protection for the ball valve mechanism provided by the farmer (a metal plate secured in place by stones), and therefore no additional protection from livestock is necessary. Four separate parts are designed which will be assembled to form the field device enclosure.



(a) Housing **(b)** Lid **(c)** Casing Mounts **(d)** PCB Support

Figure 4.18: Field Device Enclosure Parts

4.3.1. Design

Housing

The PCB enclosure is designed to perfectly fit the populated PCB, taking into account the 3D bodies and heights of the components. The casing width is designed so that the

PCB fits perfectly, with a small margin left open in the height of the casing, to easily install and remove wires from the sensors and solar panel. A screw handle is added to each side of the casing, which will be used to secure the enclosure. Screw holes with diameter 6 mm will be drilled through when installing the device onto a wooden pole, as seen in Figure 4.17b. Holes for the antenna, sensor wires and solar panel wires are drilled after the PCB is populated.

Lid

The casing lid has the same length and width as the housing, ensuring a perfect fit. Corresponding screw handles are also added and M3 screws will secure the lid and casing in place. The solar panel lies on the lid, its angle optimised as 30°, the latitude of Swellendam. The device will be mounted so that the solar panel faces North. A window will be created after manufacturing the lid, so that the LEDs can be seen when the device is in its enclosure.

Casing Mounts

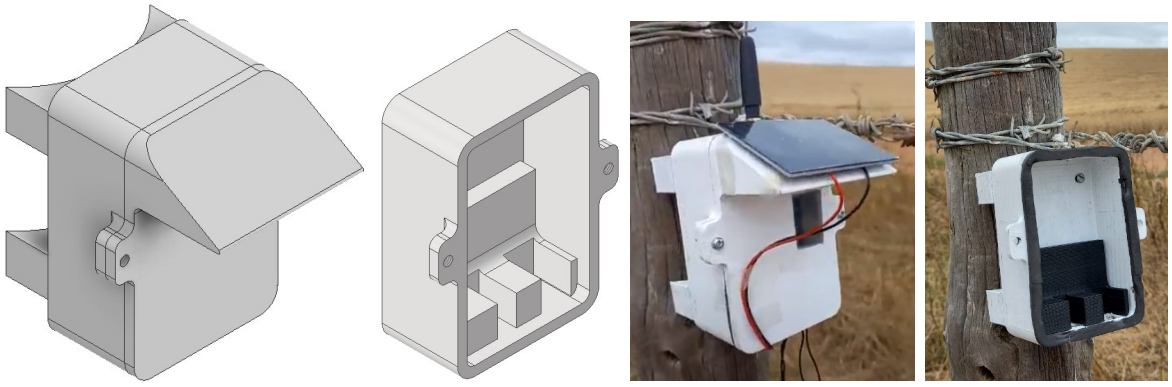
Mounts are designed to fit the rectangular enclosure perfectly onto the round pole with diameter 100 mm. Each field device will have two mounts for ensured stability. The 6 mm screw holes align with the screw holes of the housing, and the mount width is the same as the housing width, resulting in a clean and symmetric design with easy assembly.

PCB Support

The PCB support will be placed inside the housing, keeping the PCB in place. Its openings make it easy to insert and remove the sensor and solar panel cables.

4.3.2. Assembly

The field device enclosure assembly and the realised version is seen in Figure 4.19.



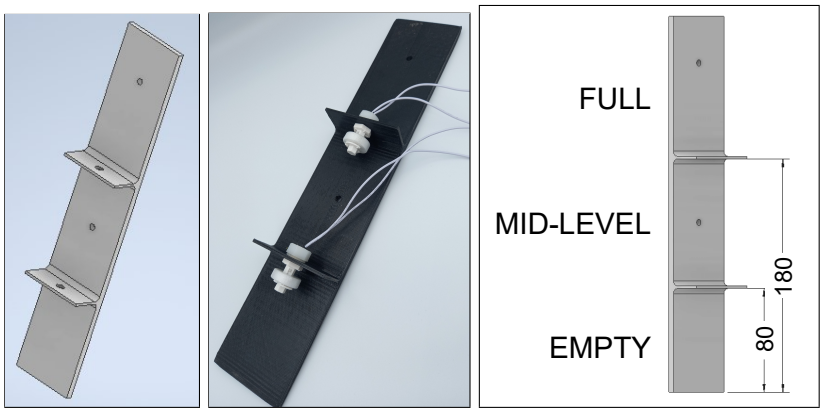
(a) Assembled Enclosure **(b)** With Support **(c)** Mounted Assembly **(d)** Mounted Support

Figure 4.19: Field Device Enclosure Assembly

4.4. Sensor Mount

The non-floating end of each reed switch sensor is fixed to desired water level thresholds. It is decided to 3D-print the sensor mounts, rather than using metal works, as it is quick to customise and can be replicated for many troughs more easily than doing metal work for each trough. Furthermore, a metal sensor mount is more prone to weather deterioration, water contamination and livestock injury than a PLA-printed mount. The sensor mount will be fixed to a trough wall near the ball valve, with the sensors screwed in place at

the desired thresholds. The water-line indicating the full water level is to be 300 mm. A farmer would be concerned about a water level below 80 mm. The threshold distinguishing the intermediate level from full threshold is selected as 180 mm. The designed and realised sensor mount, as well as the thresholds designed for, is seen in Figure 4.20

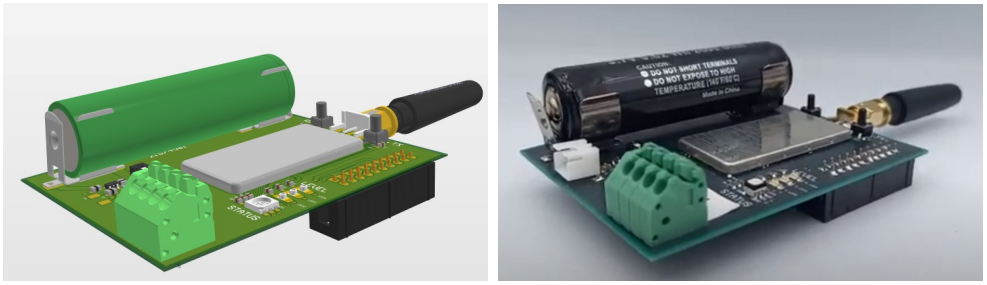


(a) Design **(b)** Mount and Sensors **(c)** Level Thresholds [mm]

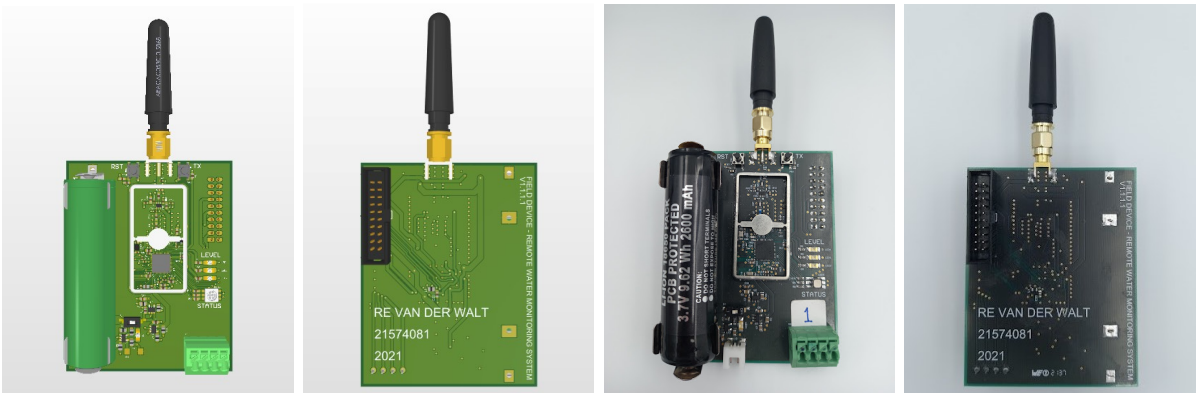
Figure 4.20: Sensor Mount

4.5. Assembly

The field device as designed and assembled is seen in Figure 4.21. The full bill of materials can be found in Appendix G. Two field devices are assembled to illustrate that the trough water monitoring solution works with multiple field devices, and can distinguish between them (refer to Chapter 7).



(a) Design **(b)** Assembled Device



(c) Design Top View **(d)** Design Bottom View **(e)** Device Top View **(f)** Device Bottom View

Figure 4.21: Field Device: Design and Assembled

Chapter 5

Field Device: Software Design

5.1. Primary Functionality

From the conversation with the farmer (W.J. de Wet, personal communication, 20 August 2021), it is concluded and agreed that sheep are at risk after 18 hours without water. Therefore, field devices will measure every six hours. This means that, should two consecutive measurements be empty, the maximum duration that the livestock could have been without water is 12 hours, giving the farmer another six hours to respond before any livestock endangerment. Every six hours, the field device takes a measurement of the trough level and writes the result to a LoRa payload. This is transmitted for 60 consecutive seconds, ensuring that the message is received by the base station. Hereafter, the device waits for another six hours.

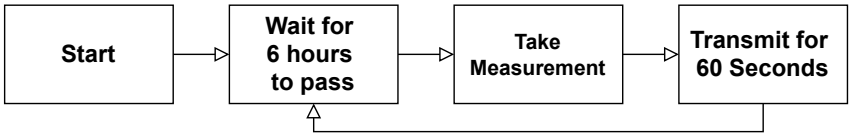


Figure 5.1: Primary Functionality of Field Device Software

5.2. Detailed Software Flow Diagram

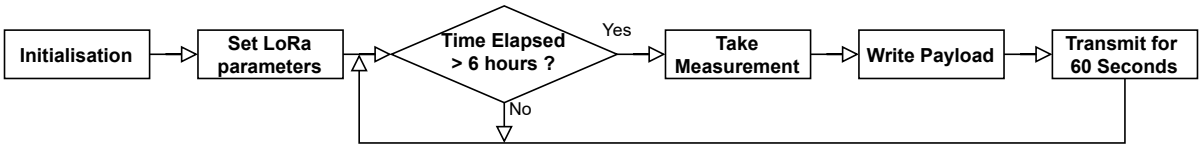


Figure 5.2: Simplified Flow Diagram of Field Device Software

5.2.1. Initialisation

The HAL drivers are initialised, including but not limited to DMA, GPIO and SubGHz. This step also initialises the clock configuration and individual pin functionalities like GPIO, interrupts and JTAG as configured for MCU hardware, seen in Figure 4.1a.

5.2.2. Set LoRa Parameters

The LoRa parameters of the MCU's SUBGHZ_PHY functionality are set as seen in Table 5.1. The spreading factor and bandwidth parameters are set to maximise output power and therefore range, trading off with packet reliability. However, due to the small size packets sent in the payload, in addition to the various checks performed to confirm a valid packet by the base station (refer to Section 7.4), and the fact that each transmitted message is sent many times for each measurement, reliability is deemed a much lower priority than range, given the agricultural application of this system. Explicit header

mode allows for variable packet lengths to be received, meaning that minimal changes would need to be made, should longer, more complex data be transmitted. It writes the payload with header as seen in Figure 5.3.

Table 5.1: LoRa Parameters Initialised

Parameter	Value	Functionality
`MODEM_LORA`	LORA	LoRa is used
`POWER`	14	Transmits at 14 dBm
`fdev`	0	Frequency Deviation N/A for LoRa
`bandwidth`	2	500 kHz
`datarate`	12	Spreading Factor
`coderate`	1	4/5
`preamblelen`	8	Preamble Length in Symbols
`fixlen`	0	Variable length packets used / Explicit header mode
`crcon`	1	Enables CRC
`freqHopon`	0	Disables intra-packet frequency hopping
`hopPeriod`	0	N/A when `freqHopon` is False
`iqInverted`	0	Not inverted
`freq`	868000000	Use 868 MHz band

5.2.3. Time Elapsed

The timer is used to check how much time has elapsed since the last measurement was made. This is checked by comparing a variable `last_meas` with the current time. If this exceeds six hours, the timer starts from zero again and a measurement is made and transmitted.

5.2.4. Take Measurement

The green status LED is set, indicating that a measurement is being made `PB6`.

The sensor EN-pins are driven high (`PB8` for top sensor, `PA1 for bottom sensor`), and the SNSE-pins are read (`PA0` for top sensor, `PA2` for bottom sensor). Based on these read values, the variables `above_bot` and `above_top` are set. From this, `measurestatus` is set, as illustrated in Table 5.2.

Table 5.2: Measurement Logic

Water Level	`above_top`	`above_bot`	`measure_status`
Empty	0	0	1
Mid-Level	0	1	2
Full	1	1	3
Error	1	0	4

When an error occurs (`above_bot=0` and `above_top=1`), `measurestatus` is set as 4. The status LED and three level LEDs are set according to the logic seen in Table 5.3. The level indicator LEDs only remain on for one second, to reduce power consumption. After transmitting, all LEDs are switched off.

Table 5.3: LED Functionality

Mode	LED2 PA5	LED3 PA6	LED4 PA7	LED5 PB5, PB6, PB7
`measurementstatus = 1`: Empty	●	●	●	●
`measurementstatus = 2`: Mid-Level	●	●	●	●
`measurementstatus = 3`: Full	●	●	●	●
`measurementstatus = 4`: Error	●	●	●	● ● ● ●
Mode: Transmitting	●	●	●	● ● ● ●

5.2.5. Write Payload

The transmitted packet consists of three bytes, and is written as seen in Figure 5.3.

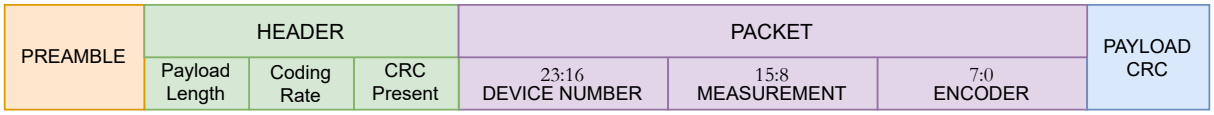


Figure 5.3: Transmitted Payload

5.2.6. Transmit for 60 Seconds

The EN-pin `PA11` for `U3` (1.5 V regulator) is set high, powering the radio. The RF switch control pins `PB12` and `PB2` are set to configure the switch into connecting the antenna with TX circuitry, seen in Table 5.4. Hereafter, a 50 ms delay is given to ensure that all transients have settled and the radio is ready to transmit. The state and control logic is displayed in Table 5.4.

Table 5.4: RF Switch Logic and MCU Control

VC1 PB12	VC2 PB2	RFC	Functionality
0	1	$RF1$	TX
1	0	$RF2$	RX

Similar to the functionality that checks whether six hours have passed as in Section 5.2.3, a variable `txtimer` is used to ensure that the device consecutively transmits for 60 seconds while flashing the blue RGB LED as seen in Table 5.3. Hereafter, the device will wait until six hours have passed.

Chapter 6

Base Station: Hardware Design

6.1. Schematic and Circuit Design

The base station receives measurements from the various troughs and displays the results graphically on a monitor. A Raspberry Pi 3 Model B+ is used as computer unit, for its low cost, simple functionality and built-in HDMI compatibility. The radio functionality is added by designing a HAT. An RFM95W, 868 MHz LoRa module is selected for its low cost and availability. It communicates to the Raspberry Pi through SPI, using the `SPI0` channel. The `MOSI`, `MISO` and `SCK` pins of the RFM module are connected to the corresponding pins on the Raspberry Pi. GPIO pins are used for the `NSS, RESET` and `DIO0` configurations, with functionalities shown in Table 6.1. The full schematic is shown in Appendix E.

Table 6.1: RFM95 Pins Connected with Raspberry Pi

RFM95 Pin	Raspberry Pi Pin	Functionality
1 `GND`	`GND` [Rail]	Reference Ground
2 `MISO`	`SPI_MISO` [21]	MISO (SPI)
3 `MOSI`	`SPI_MOSI` [19]	MOSI (SPI)
4 `SCK`	`SPI_SCLK` [23]	SCK (SPI)
5 `NSS`	`GPIO6` [31]	Active-Low Slave Select, pulled low by Raspberry Pi
6 `RESET`	`GPIO_GEN3` [15]	Active-High Reset, set high by Raspberry Pi
8 `GND`	`GND` [Rail]	Reference Ground
10 `GND`	`GND` [Rail]	Reference Ground
13 `3.3V`	`3.3V` [Rail]	Power Supply to RFM Module, supplied by Raspberry Pi
14 `DIO0`	`GPIO_GEN2` [13]	IRQ / Interrupt Request, set high by RFM Module

6.2. PCB and Physical Layout

6.2.1. Layout and Placement

The HAT is designed to be mounted on top of the Raspberry Pi. Therefore, the female headers are placed on the HAT bottom, which will fit onto the Raspberry Pi. For optimal reception using an omnidirectional antenna, a through-hole SMA connector is used, so that it will point upward. A decoupling 10 μF capacitor is added between the 3.3 V pin of the RFM95 module and GND, to mitigate transients, should it occur. The 3.3 V power track on the PCB is designed as thick as possible and the clearance around all tracks are set to 1mm, ensuring proper isolation between nets, pads and tracks, and making the soldering process easier.

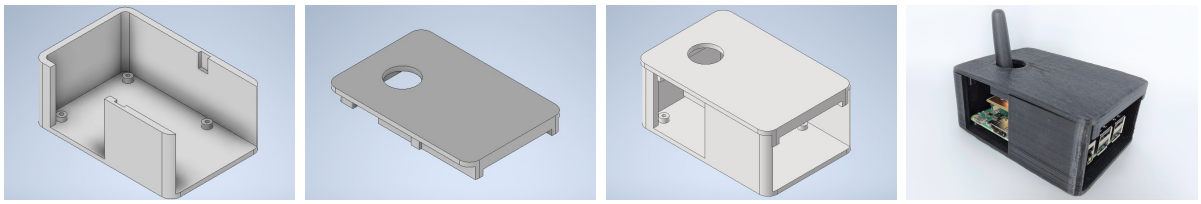
6.2.2. PCB Printing and Specifications

The optimal antenna track length is calculated using Equation 4.5, similar to the field device calculation (refer to Section 4.2). The PCB hat is printed on a double-sided FR-4 board, with substrate thickness 1.35 mm. Therefore, the calculated track width for optimal signal transfer is 2 mm. Footprints of through hole components such as the SMA connector and header mounts are adapted, making the pads longer on the outer side of the component, ensuring that it is easier to get a soldering iron onto the pad under the component while assembling. This is illustrated in Figure 6.1. The PCB is created using the university's routing machine on a double-sided FR-4 copper plate.

Figure 6.1: Thick Outer Annular Ring

6.3. Enclosure Design

A base station enclosure is designed and 3D-printed, giving it a neater appearance in the farmer's home. This is displayed in Figure 6.2.

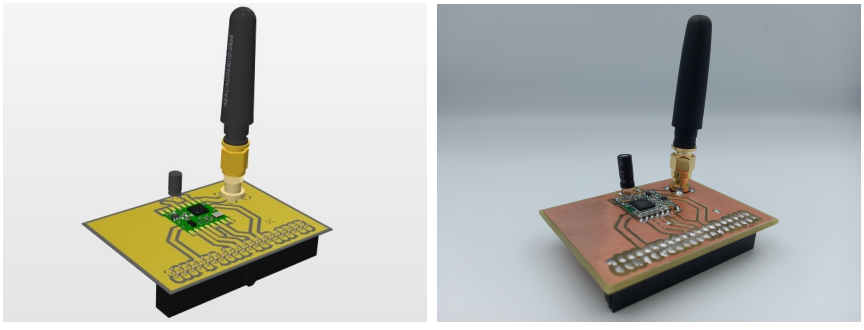


(a) Casing **(b)** Lid **(c)** Assembled **(d)** Realised

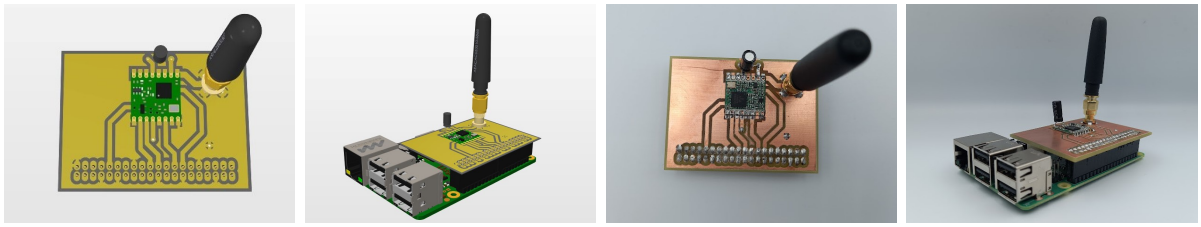
Figure 6.2: Base Station Housing

6.4. Assembly

The base station as designed and assembled is seen in Figure 6.3.



(a) HAT Design **(b)** Assembled HAT



(c) Design Top View **(d)** Design Assembled **(e)** Device Top View **(f)** Assembled Device

Figure 6.3: Base Station: Design and Assembled

Chapter 7

Base Station: Software Design

7.1. Primary Functionality

The base station acts as receiver, runs the dashboard on a monitor and warns the system owner when urgent attention is needed at one or more troughs. The receiver waits for a LoRa packet to be received. This packet is validated and, depending on which device it comes from, the received data is written to a csv file. The dashboard displays measurements from the last 48 hours, with a separate chart for each trough. This is displayed, with the measurement date and time, as seen in Figure 7.1. Additionally, a map of the farm indicates where the different troughs lie. This is shown in Figure 7.2. If a trough is measured as empty for two consecutive readings, the chart background for that trough becomes bright red, ensuring that it will grab the attention of the farmer or anyone passing by the monitor. Furthermore, the user is notified via email, specifying which troughs need attention.

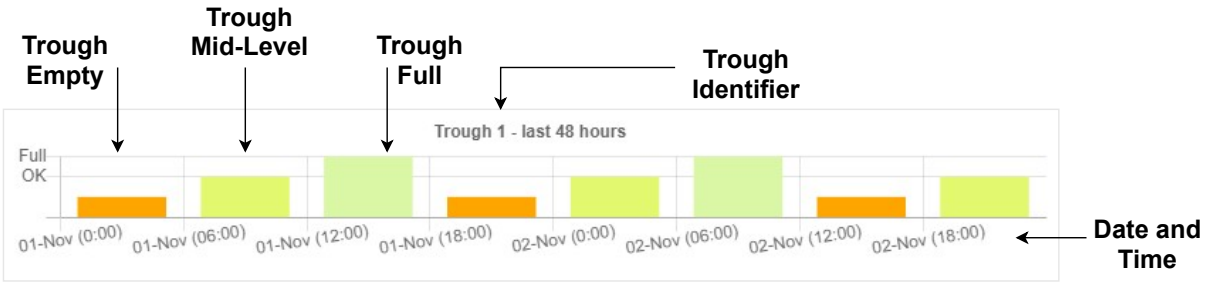


Figure 7.1: Dashboard Trough Display

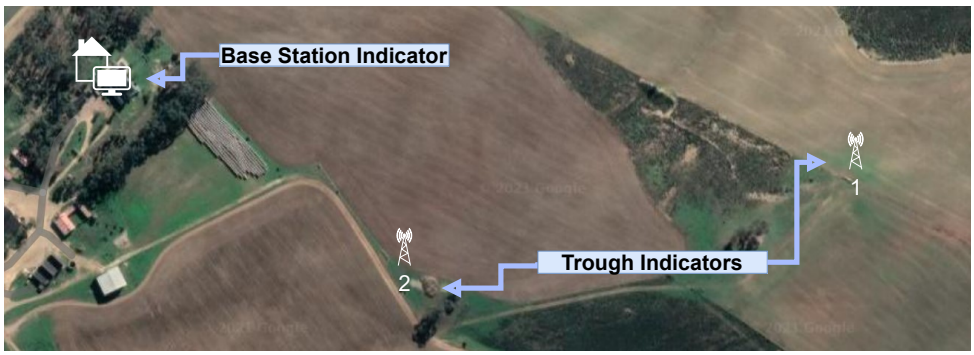


Figure 7.2: Farm Map with Allocated Trough Numbers

7.2. Flow Diagram

The primary functionality of the base station software is summarised in Figure 7.3. It is colour-coded according to the programming language that it was written in. The languages are bash script, Python, C, CSV, CSS and JavaScript. The bash script executes multiple commands, allowing the user to run the receiver and dashboard code simultaneously, by calling a single command. This is extremely useful, given that the user would typically not

be familiar with programming and command line code. The base-station software is divided and categorised according to functionality, as explained in the following subsections.

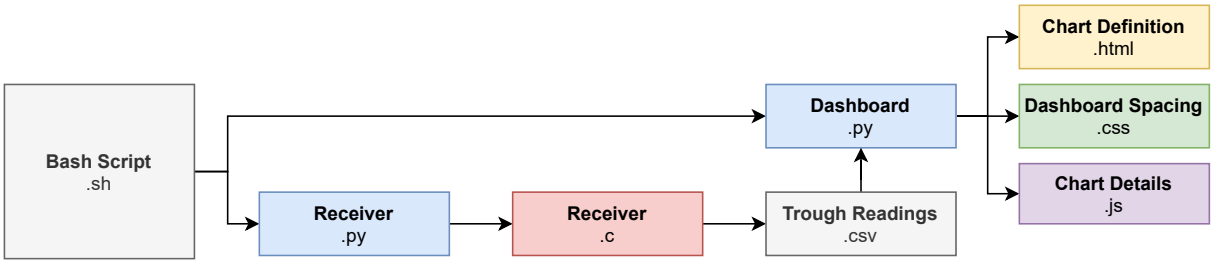


Figure 7.3: Colour-Coded Base Station Functionality

7.2.1. Receiver

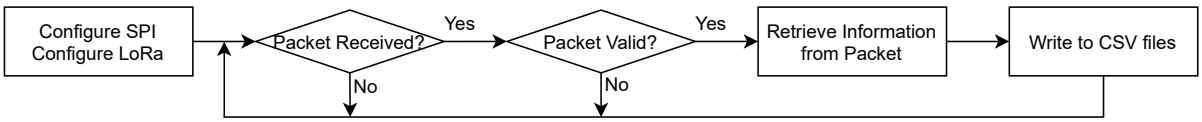


Figure 7.4: Flow Diagram of Receiving Sub-Segment

Configure SPI and LoRa

The SPI pins are configured corresponding to the hardware design (refer to Section 6.1). LoRa parameters are set the same as for the field device (refer to Section 5.2.2).

Packet Received

The device is in stand-by mode, and waits for an incoming LoRa packet. When a packet is received by the base station, an interrupt is triggered, resulting in a `True` return value.

Packet Validation

The packet is validated in three ways to ensure reliability. A CRC check is performed, internalised from the LoRa library. As it is known that the field devices will transmit packets of three bytes, a check is done to see whether the received packet is the correct size. This check eliminates false or corrupted messages, which may occur when explicit header mode and a high spreading factor is used, as in this case. Finally, the third byte of the received packet is read, and a check is performed on whether it matches the encryption byte set by the field device. This third and final byte is unique to each farm and system. This prevents systems from various farms interfering with each other. If all three of these checks pass, the packet is identified as valid and a `True` value is returned.

Retrieve Information from Packet

The first byte is read as the field device number, identifying which trough the measurements are coming from. The second byte is the mode or measurement result from the field device, with decoding as seen in Table 7.1. The third byte was used for packet validation.

Table 7.1: Received Measurements and Meanings

Byte 2 (3:0)	**Result**
0001	Empty
0010	Mid-Level
0011	Full
0100	Error

Write to CSV files

The time-stamp and measured results are written to csv files, with a respective file for each trough. This can now be accessed by the dashboard software for further processing.

7.2.2. Dashboard

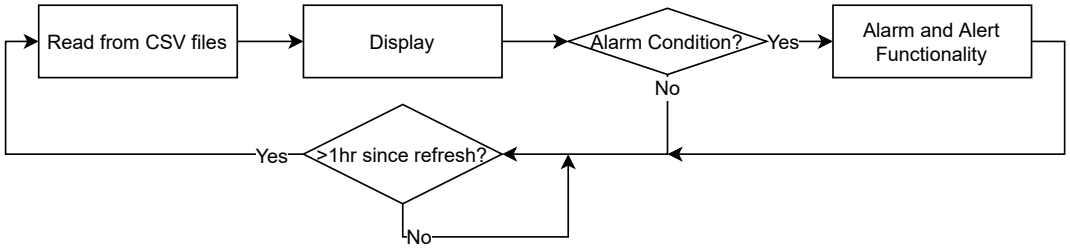


Figure 7.5: Flow Diagram of Dashboard Sub-Segment

Read from CSV Files

The eight most recently received measurements from each trough is read from the respective CSV files. This is passed as arrays to the display code.

Display

Measurements from the last 48 hours are displayed in bar chart format, colour-coded by value. Each trough is represented on its own chart. A farm map indicates where the various troughs are located, making it easy for the user to identify which camps the different trough numbers represent.

Alarm Condition

If the last two measurements from one or more troughs were empty, or an error condition is experienced at any trough, the alarm condition returns `True`.

Alarm and Alert Functionality

If the occurring alarm condition is that a trough has been empty for two consecutive measurements, that trough's chart becomes bright red, in order to grab the user's attention when passing by the monitor.

If an error measurement has been made, (when the top sensor measures as full and the bottom sensor measures as empty, meaning that the sensor mount may have fallen over), the trough measurement becomes a bright purple, to pull the user's attention.

When one or more of these error conditions occur, if the house has Wi-Fi, the base station also sends a notification to the user's preferred e-mail address. This means that results can be received remotely.

It is, however, important to note that, should the house not have internet access, the alarm functionality will still work, with the exception of notifications by e-mail.

Time since Refresh

Since measurements are only expected once every six hours from each trough, the dashboard refreshes once every hour.

Chapter 8

Tests and Measurements

8.1. Implementation

8.1.1. First Stage Implementation: Solution Development

After the design of the field device and base station, there was no way of knowing that either works, as it is needed for a working receiver to verify that the transmitter works, and vice versa. As an intermediate solution, a Nucleo development board from ST was used for developing the transmit software. Using a commercially available solution significantly reduced the likelihood of a hardware problem, therefore alleviating the transmitter software development process. An FSH4 spectrum analyser confirmed that the nucleo board was transmitting. This meant that the base station could be developed and tested without a field device. After developing the base station, the field device could be tested, knowing that the receiver works. The nucleo board does not form part of the final implementation.

8.1.2. Second Stage Implementation: Functionality Tests

Range

A range test is performed using the FSH4 hand-held spectrum analyser. Given the receiver sensitivity of -111 to -145dBm at 868 MHz [32], the test is done by walking away from the transmitting field device with the spectrum analyser until the received signal strength is -111 dBm. This ensures that the range test accounts for worst-case receiver sensitivity. Coordinates are saved at points of interest, ensuring accurate distance measurements.

The base station and field device are taken to an area on the farm with the furthest possible line-of-sight to do a practical system range measurement. The base station is left at a point and the field device is taken to the furthest hill on the farm by vehicle. Unfortunately, due to many hills in the region, this is the furthest line-of-sight measurement that could be taken.

Transmit Power

The transmit power of the assembled field device is measured by directly connecting the SMA connector of the field device to the RF_in port of the FSH4 spectrum analyser, directly measuring the power without having to account for cable or free space losses. This set-up is shown in Figure 8.1.

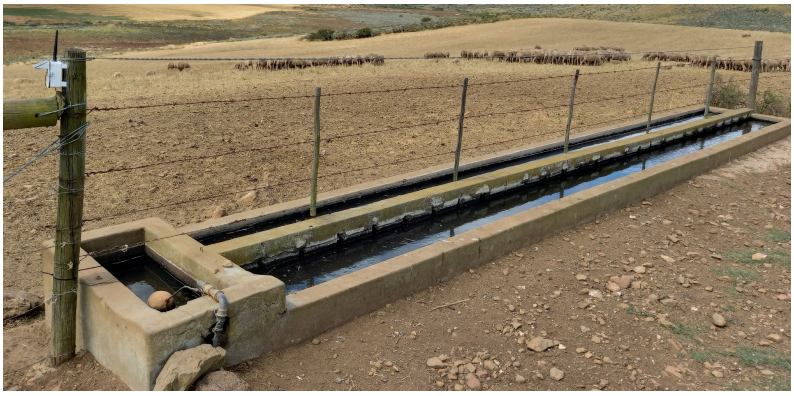
Figure 8.1: Set-up to Measure Transmit Power using FSH4

Power Consumption

To evaluate the battery lifetime and charging functionality of the field devices, the battery voltages are measured at points of interest in time using a multi-meter. The first measurement is made before any use, when first taken from its packaging. Tests, software debugging and other functional measurements are performed, while the device transmits nearly constantly, operating at its maximum power consumption for long durations of time. The battery level is again measured before the field device is installed in the field, and is expected to have reduced due to the functionality tests. After 48 hours of operation in the field and running with the solar panel and charging circuitry active, the battery voltage is measured again. A comparison of these three measurements indicates whether the solar panel charges the battery, and if the power consumption with device operation is sustainable. From Section 4.1.7, calculations indicate that the battery should recharge, even with minimal solar exposure. The results are shown in Section 9.1.3.

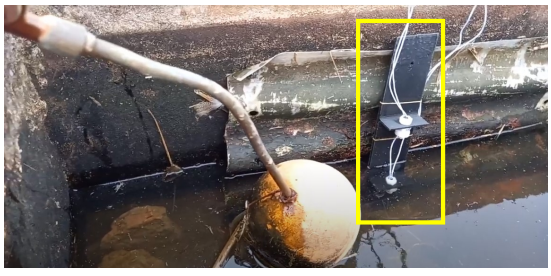
8.2. Experimental Set-Up

Tests and measurements are made on a farm near Swellendam, Western Cape. For proper illustration of the full functionality of this system, one device is mounted to a trough in a camp with sheep, and the second device is mounted at a camp where there are currently no livestock, therefore granting the ability to manipulate water levels without affecting livestock or interfering with farm activity. Trough-1 is not interfered with, and runs as a real-life, practical implementation. A ball-valve automatically refills troughs up to their full level. Therefore, it is expected that Trough-1 will almost always measure as full, and it is not expected to raise any alarm conditions. Trough-2 is manipulated to simulate error conditions, such as the trough running dry for a long duration or a faulty reading when the sensor mount falls over or a wire has snapped. Tests are run for 48 hours. In a practical environment, the user would typically only be interested in the last 6 to 18 hours of measurements. However, for this demonstration, 48 hours of data is collected to illustrate proper operation and full functionality. The experimental set-up is shown in Figure 8.2.



(a) Overview

(b) Field Device



(c) Sensor Mount in Water

Figure 8.2: Experimental Set-up on Farm

Chapter 9

Results

9.1. Functionality Tests

9.1.1. Range

Even after moving to the furthest possible line-of-sight point on the farm, the base station still successfully received each transmitted message. The horizontal distance from the base station to the top of the hill is measured, using coordinates, is 2.9 km, seen in Figure 9.1. The white dot denotes the hill's peak, from which the field device transmits, whereas the blue dot denotes the base station / receiver at the farmer's home.

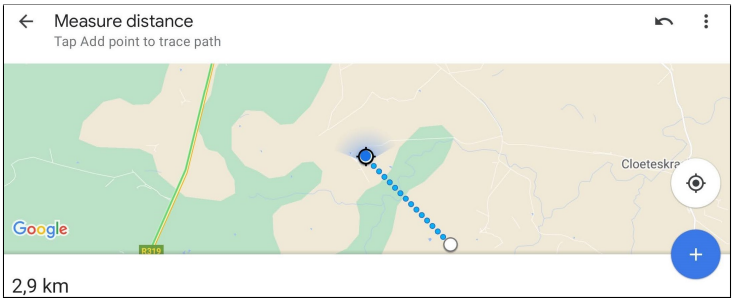


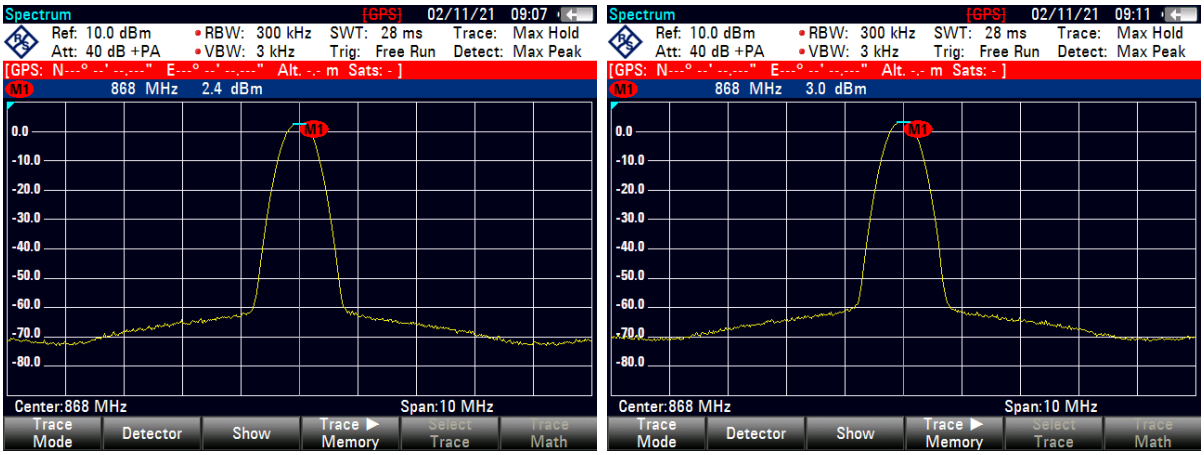
Figure 9.1: Range Measurement, 7 November 2021

This proves that the system should work within a 3 km radius, possibly further. This range proves sufficient, easily meeting the range objective for the project. South African livestock farms do not typically span wider than this range, and the solution therefore proves more than sufficient. A further range test is not necessary, as the results exceed the range objective for this project as described in Section 1.2.

9.1.2. Transmit Power

The results from the spectrum analyser are shown in Figure 9.2.

Device-1 has an output power of 2.4 dBm, and Device-2 outputs 3 dBm. These differ with 0.6 dBm, which is noticeable, considering that the same design, PCBs, components and assembly was followed. This testifies to the sensitivity of this RF circuitry. Furthermore, both field devices transmit at a much lower power than the software-configured 14 dBm as expected. This is considered a side effect from component compromises which had been made, where alternative components had to be sourced due to a two month wait for ordered components. Unfortunately, these components play a crucial role in the RF sub-circuitry, and can be considered to have had an influence on the true output power capability of the field devices. This is discussed further in Section 10.3.



(a) Device-1 (2.4 dBm) **(b)** Device-2 (3.0 dBm)

Figure 9.2: Transmit Power Measured with FSH4

9.1.3. Power Consumption

The battery voltage is measured at intervals as described in Section 8.1.2 to evaluate whether the charging circuit is working and the power consumption calculations are correct.

Table 9.1: Battery Measurements

	New	Before Test	After 48 hours
Battery 1	3.67V	3.49V	3.69V

It should be noted that, on the days of testing and implementation, the weather was cloudy and rainy, representing a worst-case scenario. The fact that the battery still increased in charge despite this, confirms that the device's power consumption is sustainable for long term use.

9.2. Experimental Set-Up

9.2.1. Trough-1

The displayed dashboard results for Trough-1 is seen in Figure 9.3. As it is not interfered with, and has an refilling ball valve, the results reflect the expected scenario, with Trough-1 always measuring as full.

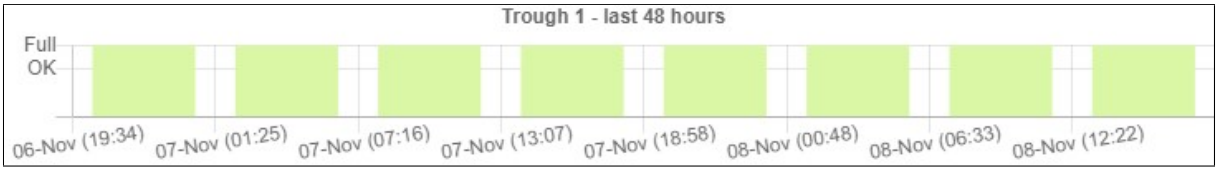


Figure 9.3: Resulting Display from Trough-1

9.2.2. Trough-2

Full Water Level

When the trough levels measured are full, the results display similar to Figure 9.3.

Empty

A single empty measurement does not raise alarm. However, when Trough-2 was left empty for longer than 12 hours, and two consecutive empty measurements were taken, the trough chart's background displays bright red, as it should, depicted in Figure 9.4.

Figure 9.4: Alert Display for Trough-2

Notification

An e-mail notification is successfully sent to the set addresses. These notifications are received as seen in Figure 9.5.

troughlevelalerts@gmail.com Fri, Nov 5, 8:17 AM
to

From: troughlevelalerts@gmail.com

To: 21574081@sun.ac.za, rietsvdw@gmail.com

Subject: Urgent Trough Alert

Please review the following trough alerts:

Trough 1: OK
Trough 2: EMPTY

Figure 9.5: E-Mail Alert Received

Error

When an error measurement is made, which could occur when one or more of the sensor cables have snapped or if the sensor mount has fallen over, leading to incomprehensible measurements, an error is reported by the field device and that measurement displays as dark purple, indicating an error condition, as expected. This is displayed in Figure 9.6.

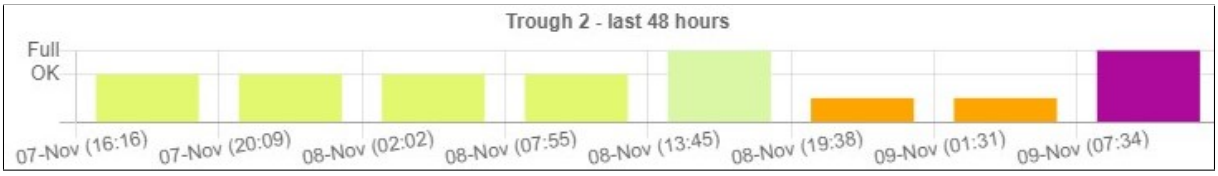


Figure 9.6: Error Measurement Display (Trough-2)

Chapter 10

Conclusion

10.1. Overview

This project aimed to develop a remote water monitoring solution using a wireless, long-range, low-power communication protocol, LoRa, which adequate in a South African context, where cellular reception is often limited. This provides an alternative to driving around from camp to camp every day, merely checking whether trough water levels are full.

The design, assembly and implementation, albeit not without challenges, was completed successfully, and results in a working prototype with the desired functionality. Individual functional test results exceed expectations and minimum requirements, and the overall system works as designed for.

The successful design and development of this water monitoring system leads to a solution for the problem addressed. It can be implemented without dependency on any existing networks or infrastructure, on any farm, and will aid in the monitoring of multiple water troughs on that farm. This will save many farmers time, effort and money, prohibiting loss of livestock.

10.2. Objectives and Metrics

The range metric of 1.5 km was easily met, with the measurement of 2.9 km as seen in Section 9.1.1. The metric for battery life and power consumption is also achieved, with calculations indicating that the batteries will only have to be replaced after expiration, and will not run flat due to power consumption reasons.

The system is proven to work with multiple field devices, independently from any cellular reception. Measurements are made at the set time intervals, and the alert and notification functionality works as expected. The device enclosure is rain-proof, wind-proof and UV-protected, making it a weather-proof solution, suitable for long term outdoor exposure. It is also out of reach from livestock, therefore meeting the animal-proof objective as well.

A base station is also successfully implemented, with data captured and analysed as expected. With the development of a display dashboard for an easy interpretation, the base station displays water-trough levels, which are automatically updated every 6 hours. Fault conditions are also successfully identified, with the user immediately informed visually by the base station dashboard and by means of an emergency email.

From the above, it is clear that all objectives as specified in Section 1.2 were met.

10.3. Problems Encountered

10.3.1. Component Shortages

The recommended HSE to use in the MCU design, per its data sheet, is a TCXO [13], but due to an international shortage, an XO is used as high-speed external oscillator. This alternative proved sufficient for this low-power transmitting application. Frequency drift issues due to temperature fluctuations are not as significant as it would have been in a high-power application. To further compensate for this, a thermal barrier was used in the PCB design, described in Section 4.2.

10.3.2. Component Delays

Component delays had, by a great margin, the most significant impact on this project. Specific RF components such as capacitors and inductors were delayed by more than two months, and alternative components had to be sourced and used in critical parts if the design. This had an impact on RF performance and is a plausible contributing factor to the transmit power output which was lower than the designed value.

Furthermore, only two of the three ordered 2 dBi antennas arrived, and a 0 dBi antenna had to be used for Trough-1, which happened to be the furthest away from the base station. However, despite this, all measurements were received, testifying to the success of this project and field device design.

The rechargeable batteries originally ordered were also delayed and eventually cancelled due to a long lead time, and alternatives had to be found.

10.3.3. Limited Documentation

During the design stage (August 2021), limited documentation was available, including design guides, reference sheets and sample applications. Interestingly, some application documents and guides were made available on the ST website shortly after, including a guide ”How to build a LoRa application using STM32CubeWL”, (1 November 2021) [33]. Many of these guides were uploaded in September to November 2021, after components were ordered. These documents suggested a similar approach and design than what was used for this project, confirming the implementation as correct.

10.3.4. Nucleo Board Transmit Power

At the time of development, the transmit power of the Nucleo board was measured as -11 dBm. This resulted in a range of less than eight meters, indicating a fault with the Nucleo board hardware. This also meant that the Nucleo board could not be used for practical implementation, should the field device not work, making it unsuitable as a back-up field device. However, despite the low transmit power and range issues, the Nucleo board could be used for debugging and development of a working receiver at a close range.

10.3.5. LoRa Module Programmability

While developing the base station software, it was found that a LoRa module had been selected and designed for, which was not programmable using Python or C, but only

low-level, assembly coding could be done to access registers and receiver data. Therefore, because of time constraints, it was decided to purchase an alternative module. Therefore, the RFM95W module was selected, as described in Chapter 6. A new PCB and schematic design was conducted.

10.3.6. Field Device Software Example Projects

At the time of field device software development, upon closer inspection of example projects and libraries provided by ST, it was found that these projects were solely configured to transmit data received through UART (universal asynchronous receiver-transmitter), not allowing for any form of message modification or implementation. The available example project was created for demonstration of the chip functionality and not for development purposes, therefore not allowing parameters to be changed freely. This meant that software examples could not be used or implemented, and the software had to be configured from scratch, by sourcing and using low-level HAL libraries, middleware and individual functions. This was very time-consuming and had a very significant impact on the time scale of this project. Ironically, by the time of having created a working software solution, the ordered field device components had still not arrived.

10.4. Future Work and Recommendations

10.4.1. Improvements on System

This was a successful first version of a potential ground-breaking solution. To get this product ready for large-scale implementation and manufacturing, or merely to build on this, a few adoptions or alterations could be made to improve on overall functionality and user operability.

10.4.2. Sensor Mount

For data illustration purposes, two sensors were used per trough, indicating three distinct water levels. In a practical setting, however, the user would merely be interested in the lower threshold. Therefore, in a larger-scale application, the sensor mount and system would be designed to only implement one sensor, therefore saving on cost.

LED Functionality

The field device LEDs are for prototyping purposes only and will not be necessary in a final product. Although the power consumption is low enough that, even with the full LED functionality, battery lifetime is not a problem. A possible alternative would be a single LED lighting upon initial start-up, as an indication to the user that it is switched on.

Bi-Directionality

It may be useful to implement bi-directional communications between the base station and field devices. This grants the ability to send ACK signals (acknowledge), preventing that a measurement is missed or not received by the base station. Additionally, this opens the possibility of remote programmability and parameter alterations or modifications.

User Interaction

The dashboard could be modified to allow for user interaction, granting the ability to change the frequency of measurements, measure distances or modify the e-mail address to send alerts to. The user can also be allowed to remotely request a measurement from a specific trough. This will ensure that the user does not have to wait for six hours to confirm whether an alarm situation has been resolved, and can check whether troughs have started filling up after it was reported to be fixed. This opens the door for live functionality and interaction.

Base Station Power-On

A useful functionality, given the South African context, is to implement functionality where the base station automatically starts to run when powered. This was emphasized, as during the time of implementation and testing, load shedding occurred frequently. This meant that, to prevent a measurement or message from being missed, the program had to be started up every time that the power came back on. This occurred multiple times a day. In a practical set-up, the user would not be willing or able to do this, and measurements will be missed. It is therefore crucial that, when the base station is powered, it should automatically run the dashboard and receiver. An alternative to this could be to have a click-able launch button, as opposed to running the program from command-line. This was merely not attended to, because of the time constraints of this project.

Audio Alarm Functionality

Another useful add-on would be to add a speaker to the base station, with repetitive sound functionality such as ten beeps every hour. This would mean that, should the farmer not be in his office during the day to see the monitor, or be without cellular reception and unable to receive emails, the base station would still grab the attention of the user or their family members.

10.4.3. Additional Implementations

Apart from trough-water monitoring, this solution could also be implemented in various other solutions, including, but not limited to, multiple agricultural applications, or any setting where water-level measurements are required.

Dam and reservoir levels could be measured by merely implementing level sensors. This will help to detect pipe leaks and assess water levels after rainy weather, as well as where water should be transported to. This could also be used to detect water overflow on certain critical areas, where a full measurement, indicating overflow, triggers an alarm condition. Furthermore, water levels of irrigation systems and vehicles could be measured. Replacing the reed switch sensors with a flow meter could be implemented to detect blockages in pipes, something that is currently done manually.

All of the above applications require minimal changes to the existing field device and base station, testifying to a successful generic design, with the potential to improve the lives of farmers across the country.

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Appendix A

Project Planning Schedule

Planned Project Timeline

21-07-2021 to 29-07-2021	Research on communication protocols, `SigFox`, `LoRa`, as well as water measuring sensor types and methods.
30-07-2021 to 31-07-2021	Make final decision on communication protocol and sensor type to use
01-08-2021 to 19-08-2021	Design field device schematic and RF sub-circuit
20-08-2021 to 22-08-2021	Visit farm where device will be implemented and measure troughs, poles. Discuss solutions, as well as the needs from a farmer's perspective. Decide on mounting techniques and frequency of measurements.
23-08-2021 to 29-08-2021	Field device hardware design and component selection. Ordering of field device components.
30-08-2021 to 02-09-2021	Design base station schematic and component selection. Ordering of base station components.
03-09-2021 to 12-09-2021	Field device and base station software design and development using Nucleo board
13-09-2021 to 03-10-2021	Assembly of field device and base station. Debugging of system and functionality tests.
04-10-2021 to 17-10-2021	Data collection on farm near Swellendam. Implementation, simulation and data sourcing.
18-10-2021 to 14-11-2021	Write report

Realised Project Timeline

21-07-2021 to 29-07-2021	Research on communication protocols, `SigFox`, `LoRa`, as well as water measuring sensor types and methods.
30-07-2021 to 31-07-2021	Make final decision on communication protocol and sensor type to use
01-08-2021 to 19-08-2021	Design field device schematic and RF sub-circuit
20-08-2021 to 22-08-2021	Visit farm where device will be implemented and measure troughs, poles. Discuss solutions, as well as the needs from a farmer's perspective. Decide on mounting techniques and frequency of measurements.
23-08-2021 to 02-09-2021	Field device hardware design and component selection.
03-09-2021 to 12-09-2021	Base station hardware and schematic design, component selection. Field device software design using Nucleo board.
13-09-2021 to 03-10-2021	Software development during field device component delay. Base station assembly.
04-10-2021 to 13-10-2021	Base station assembly and software development to a working stage. Still waiting for field device components and replacements.
18-10-2021 to 28-10-2021	Start with report while waiting for field device components. Received alternative components and it is assembled.
29-10-2021 to 3-11-2021	Preparation for testing on farm. Waterproofing, mounting, functionality tests performed.
4-11-2021 to 8-11-2021	Testing and implementation on farm near Swellendam
9-11-2021 to 14-11-2021	Final report writing

Appendix B

ECSA Outcomes Compliance

ELO 1 - Problem Solving

An ill-defined, vague problem faced by South African farmers was conceptualised and transformed into a problem statement. This was further divided into measurable and/or observable objectives, therefore understanding what is necessary to solve this problem, seen in Section 1.2. A solution was conceptualised, as displayed in Chapter 3, and solved, with the results discussed in Section 1.3 and Section 10.1.

ELO 2 - Application of Scientific and Engineering Knowledge

Crucial electrical and electronic engineering knowledge was applied when doing circuitry design in Chapters 4 and 6. Mathematical understanding was required to conceptualise the effects and workings of logarithmic RF power and antenna radiation. Furthermore, mathematical and engineering understanding was required when interpreting and analysing various data sheets when designing in Chapter 4, to grasp and anticipate trade-offs between various parameters and variables.

ELO 3 - Engineering Design

Engineering design played a pivotal role in the success of this project. A complex hardware schematic design from MCU level was conducted in Chapter 4, considering multiple and complex parameters. This included design of a complicated RF circuit, power supply and many other functionalities. A hardware and software design was conducted for both the field device and base station. Since there were minimal similarities between the two designs (different MCUs, logic and programming languages used), completely separate and distinct designs were conducted, effectively resulting in four chapters with significant showcasing of engineering design (Chapters 4 to 7). Furthermore, enclosures, mounts and assembly components were designed for both the field device and base station, described in Sections 4.3, 4.4 and 6.3. Creative solutions had to be found, especially for the field device enclosure, to mount a rectangular housing to a round pole, while taking into account the necessary antenna dipole-placement and required solar panel orientation, yet still being able to measure water levels and keep the entire device outdoor-proof.

ELO 4 - Investigations, Experiments and Data Analysis

In order to test and debug the field device, many individual functional tests were performed, as described in Chapter 8. Additionally, the system was implemented in a real-world scenario on a farm, collecting data and observing the response to various simulated scenarios. Results were analysed and conclusions were made about what is indicated by these results, as well as possible causes when results were not as expected, seen in Chapter 9.

ELO 5 - Engineering Methods, Skills and Tools, Including Information Technology

PCB design, conducted for the field device and base station in Sections 4.2 and 6.2, required the use of Altium Designer and the S103 Routing Machine. The various enclosures and mounts as seen in Sections 4.3, 4.4 and 6.3 were created using AutoDesk Inventor Professional, another engineering software, and 3D-printed. For the field device PCB population, fine soldering was required using a microscope for small components, especially the RF subcircuitry. Constant continuity tests were conducted using a multi-meter. Self-evaluation methods and tests were designed to check various functionalities at different stages in the design and development phases, seen in Section 8.1.1, where a development board was used as intermediate solution to aid with the design and development of the base station and field device.

Furthermore, spectrum analysers and spectrometers were used in the antenna labs, using specialised equipment to check very specific properties of antennas and transmitted signals, as briefly mentioned in Section 8.1.

Software development for the field device required the use of STM32CubeIDE and STM32CubeProgrammer, to write software and program field devices. An ST-Link/V2 software development device was used to program the field device.

ELO 6 - Professional and Technical Communication

The writing of this report, in addition to the presentation and demonstration video on this project, proves this learning outcome to be achieved.

ELO 8 - Individual Work

With the exception of weekly meetings with the project supervisor, this project was done in its entirety by myself (R.E. van der Walt). Although opinions of others with experience in specific knowledge fields were consulted at times, all designs and decisions were made individually.

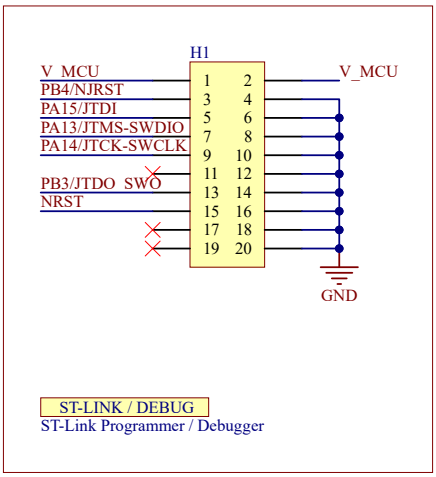
ELO 9 - Independent Learning Ability

In Chapter 2, the ability to learn outside of the undergraduate department and degree of Electrical and Electronic Engineering is displayed through research into various communication protocols, water level measuring techniques and existing solutions. Furthermore, as displayed in Section 4.1.2, various dielectrics and important RF parameters were investigated. Learning to use Altium Designer and conducting a PCB design was done independently. Additionally, considering the broad scope of work and knowledge areas this project covers, work covered in undergraduate modules that were not a part of my (R.E. van der Walt) undergraduate studies, which had to be self-studied. This includes, but is not limited to solar panel and charge controller circuits (energy and power systems) in Section 4.1.7, the design and implementation of a dashboard (web development and informatics) in Section 7.1 and the RF circuit design and component selection (telecommunications) in Section 4.1.2. This indicates the ability to self study and educate on complex topics outside of the structured undergraduate degree programme.

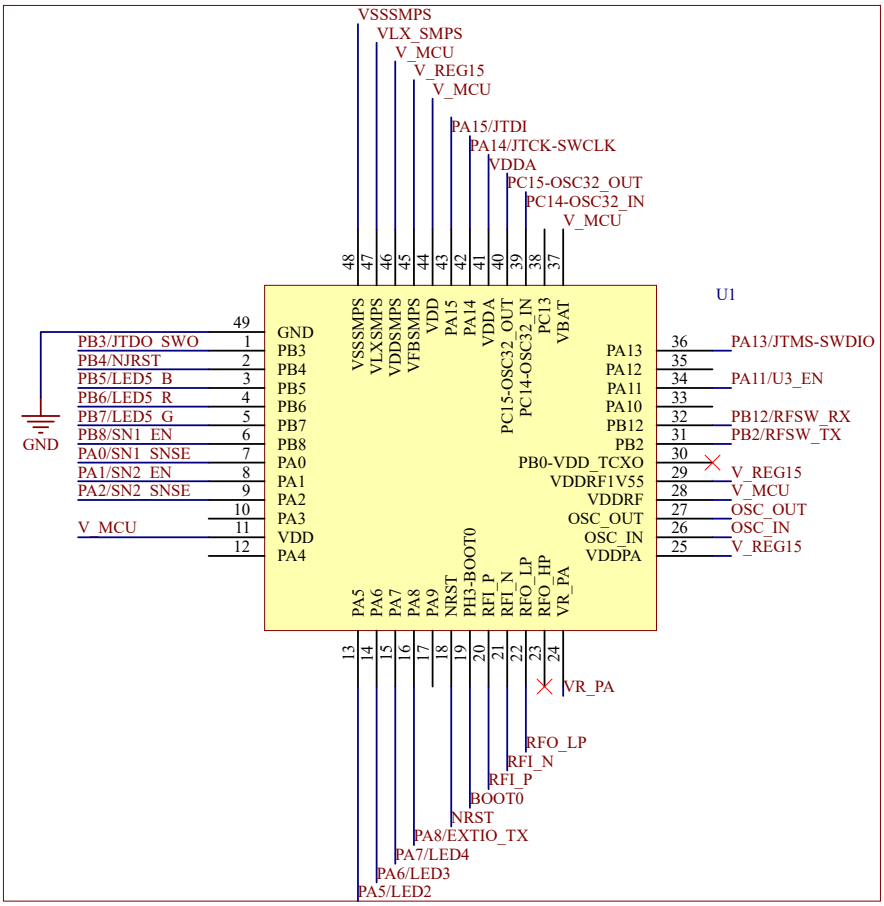
Appendix C

Field Device Schematic

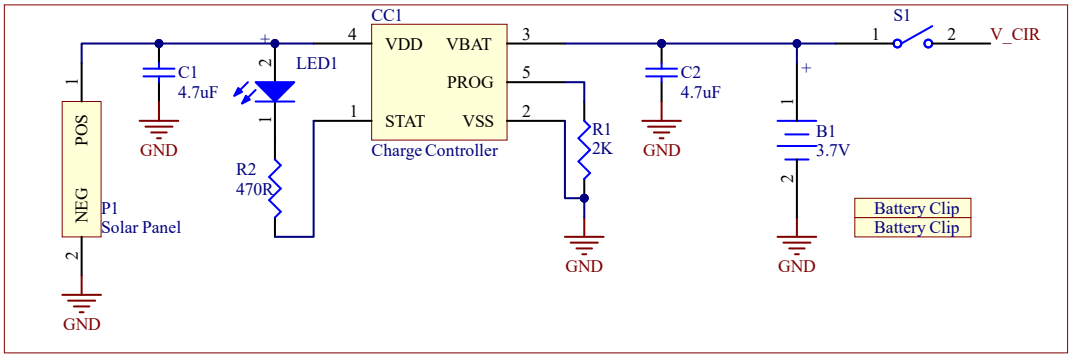
JTAG



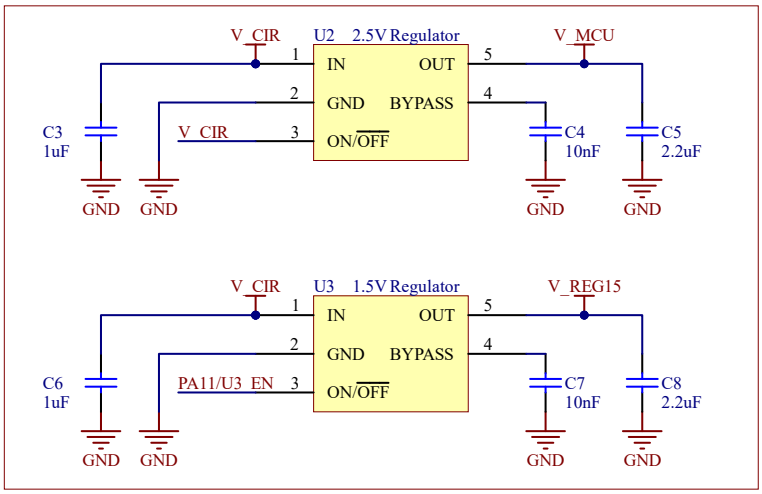
MICROCONTROLLER



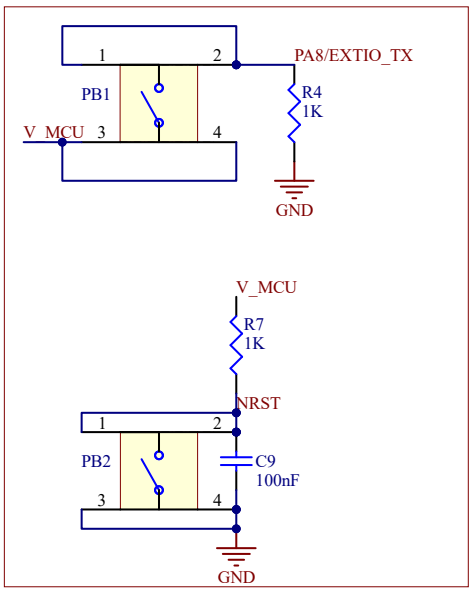
BATTERY



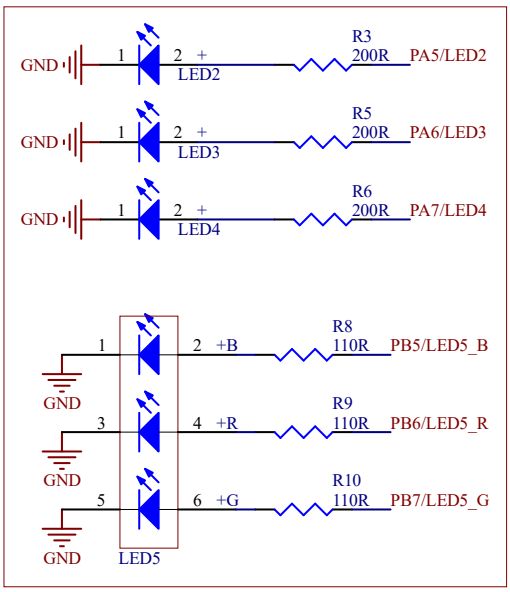
VOLTAGE REGULATION



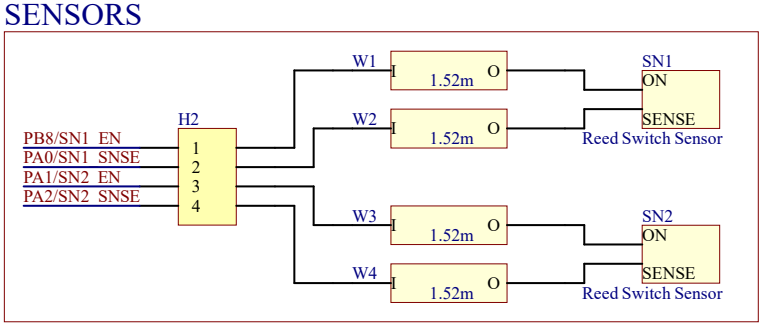
PUSHBUTTONS

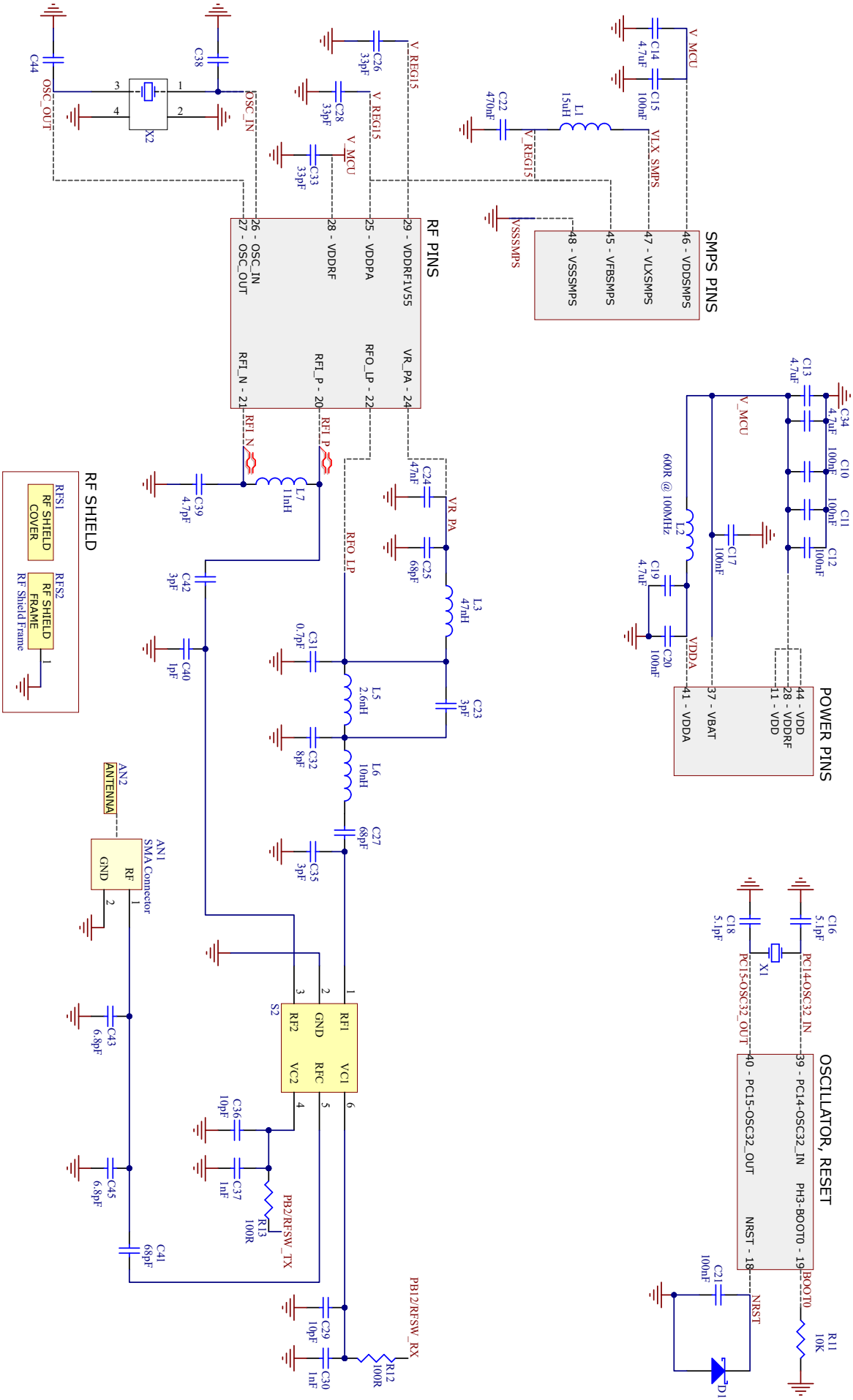


LEDs



SENSORS

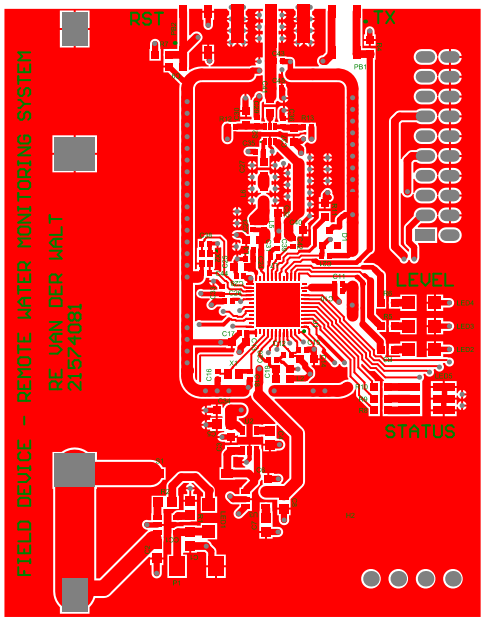



SMPS PINS
V_MCU
C14 4.7uF
C15 100nF
VLX_SMPS
L1 15uH
C22 470nF
V_REG15
VSSSMPS
46 - VDDSMPS
47 - VLXSMPS
45 - VFBSMPS
48 - VSSSMPS
POWER PINS
C13 4.7uF
C34 4.7uF
C10 100nF
C11 100nF
C12 100nF
C17 100nF
L2 600R @ 100MHz
C19 4.7uF
C20 100nF
VDDA
44 - VDD
28 - VDDRF
11 - VDD
37 - VBAT
41 - VDDA
RF PINS
C26 33pF
C28 33pF
C33 33pF
C38
C44
OSC_OUT
OSC_IN
X2
29 - VDDRF1V55
25 - VDDPA
28 - VDDRF
26 - OSC_IN
27 - OSC_OUT
VR_PA - 24
RFO_LP - 22
RFI_P - 20
RFI_N - 21
C24 47nF
C25 68pF
VR_PA
RFO_LP
L3 47nH
C23 3pF
C31 0.7pF
L5 2.6nH
C32 8pF
L6 10nH
C27 68pF
C35 3pF
C39 4.7pF
L7 11nH
C42 3pF
C40 1pF
RFI_N
RFI_P
RF SHIELD
RFS1
RF SHIELD COVER
RFS2
RF SHIELD FRAME
RF Shield Frame
OSCILLATOR, RESET
C16 5.1pF
C18 5.1pF
X1
PC14-OSC32_IN
PC15-OSC32_OUT
39 - PC14-OSC32_IN
40 - PC15-OSC32_OUT
PH3-BOOT0 - 19
NRST - 18
C21 100nF
NRST
BOOT0
R11 10K
D1
AN2
ANTENNA
AN1
SMA Connector
RF
GND
C43 6.8pF
C45 6.8pF
C41 68pF
S2
RF1
GND
VC1
RF2
RFC
VC2
C36 10pF
C37 1nF
R13 100R
PB2/RFSW_TX
C29 10pF
C30 1nF
R12 100R
PB12/RFSW_RX

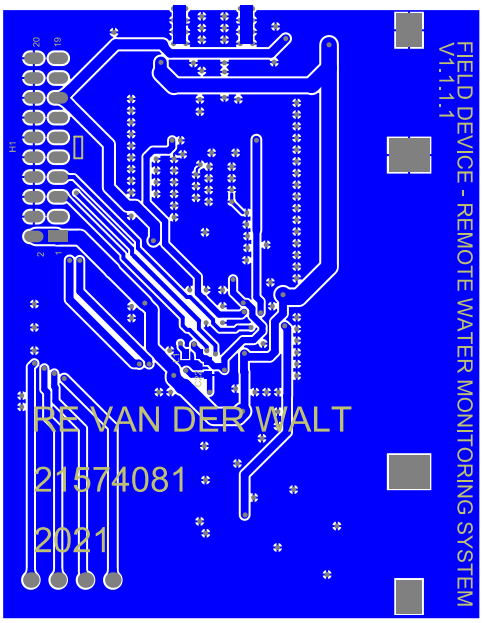
Appendix D

Field Device PCB Design

Top Layer

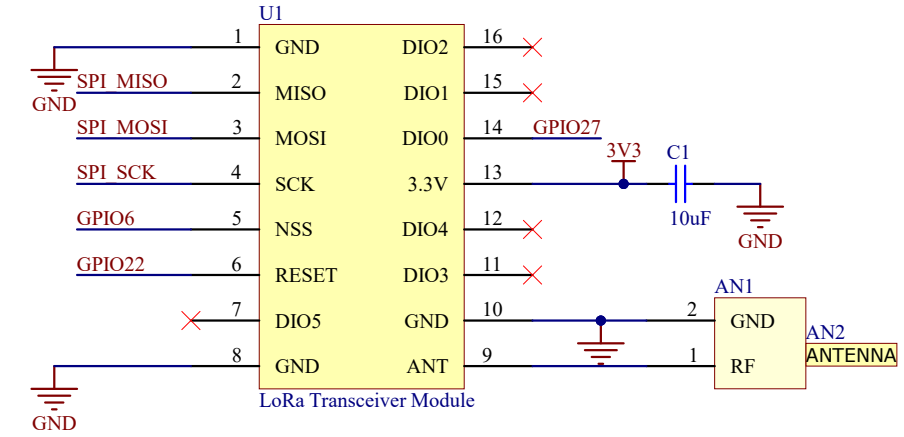


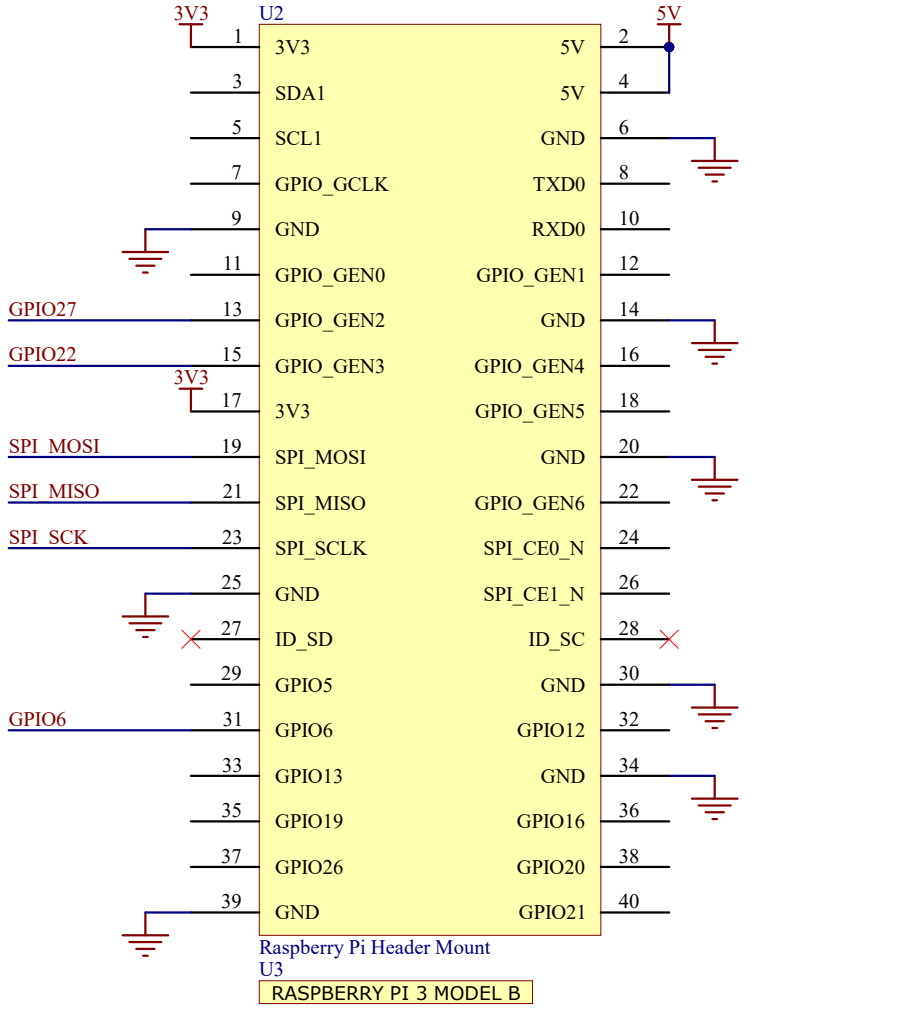
Bottom Layer



Appendix E

Basestation Schematic

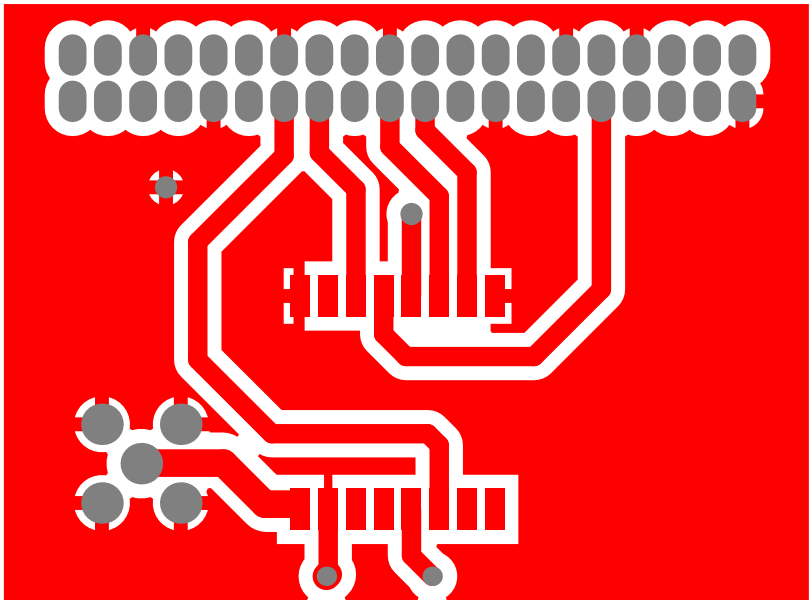




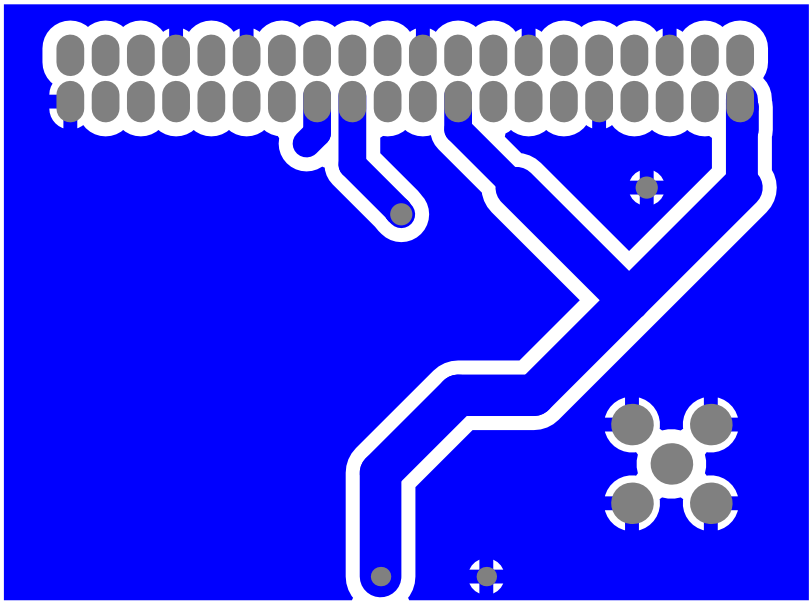
Appendix F

Base Station PCB Design

Top Layer



Bottom Layer



Appendix G

Bill of Materials

G.1. Field Device

G.1.1. Miscellaneous

Category	QTY	Designator	Description	Part No.	Package	Manufacturer	Price (ZAR)
RF Circuit	1	AN1	SMA Connector	CONSMA001-C-G		Linx Technologies Inc.	37.14
	1	AN2	RF Antenna	AEACAC053010-S868		Abracon LLC	89.84
	1	RFS1	RF Shield Cover	MS409-10C		Masach Tech Ltd.	19.98
	1	RFS2	RF Shield Frame	MS409-10F		Masach Tech Ltd.	21.02
Power Supply	1	B1	Rechargeable Battery	ICR-18650 22P		Samsung	146.99
	1	CC1	Charge Controller	MCP73831T-3ACI OT	SOT23-5	Microchip Technology	8.70
	2	CLIP1, CLIP2	Battery Holder Clip	254		Keystone Electronics	9.73
	1	D1	TVS_2 - DIODE	CPDT-5V0U-HF	SOT-23-3	Comchip Technology	4.44
	1	P1	Solar Panel	313070004		Seeed Studio	40.93
	1	S2	RF Switch	CG2179M2-C4		CEL	10.47
Development and Debug	1	DB1	ST-Link Programmer / Debugger	ST-LINK/V2		STMicroelectronics	383.00
	1	H1	JTAG Header 20-Pin	61202021621		Wurth Elektronik	13.12
Sensors	1	H2	4-pin Wire Screw Terminal	1984989		Phoenix Contact	10.34
	2	SN1, SN2	Reed Switch Sensor	PLS-020A-3PPI		PIC GmbH	86.38
	4	W1, W2, W3, W4	Extension Wire	C2003A.12.01		General Cable/Carol Brand	9.36
General Functionality	4	LED1, LED2, LED3, LED4	Green LED	APTL3216ZGCK		Kingright	9.48
	1	LED5	RGB LED	150505M173300		Wurth Elektronik	9.03
	2	PB1, PB2	Tactile Switch	PTS 647 SN70 SMTR2 LFS		C&K	1.93
	1	S1	Maintenance DIP Switch	DS04-254-2-01BK-SMT		CUI Devices	8.99
MCU	1	U1	STM32WL55CC Microcontroller	STM32WL55CC		ST Microelectronics	
	1	X1	Crystal Oscillator	NX2012SA 32.768KHz EXS00A-MU00527	2-SMD	NDK America, Inc.	13.41
	1	X2	XO Crystal - 32MHz	NX2016SA-32MHZ-EXS00A-CS11336		NDK America, Inc	8.55
Voltage Regulation	1	U2	2.5V Regulator	LP2985-25DBVR	SOT23-5	Texas Instruments	8.60
	1	U3	1.5V Regulator	LP2985AIM5-1.5/NOPB	SOT23-5	Texas Instruments	13.04

G.1.2. Capacitors

QTY	Designator	Description	Part No.	Package	Voltage Rat	Value	Tolerance	Type	Manufacturer	Dielectric / Temp Coeff	Price (ZAR)
2	C1, C2	4.7uF Capacitor	CL21A475KOFNNNG	0805	16V	4.7uF	10%	Ceramic	Samsung Electro-Mechanics	X5R	1.92
2	C3, C6	1uF Capacitor	CC0603JRX7R6BB105	0603	10V	1uF	5%	Ceramic	YAGEO	X7R	3.98
2	C4, C7	10nF Capacitor	C0805C103J5GEC7210	0805	50V	10nF	5%	Ceramic	KEMET	C0G, NP0	4.57
2	C5, C8	2.2uF Capacitor	885012207079	0805	25V	2.2uF	10%	Ceramic	Wurth Elektronik	X7R	3.24
1	C9	100nF Capacitor	CL10B104KB8VPJC	0603	50V	100nF	10%	Ceramic	Samsung Electro-Mechanics	X7R	2.21
7	C10, C11, C12, C15, C17, C20, C21	100nF Capacitor	CC0402KRX7R7BB104	0402	16V	100nF	10%	Ceramic	YAGEO	X7R	1.70
4	C13, C14, C19, C34	4.7uF Capacitor	CC0603KRX5R7BB475	0603	16V	4.7uF	10%	Ceramic	YAGEO	X5R	3.39
2	C16, C18	5.1pF Capacitor	CC0402CRNPO9BN5R1	0402	50V	5.1pF	0.25pF	Ceramic	YAGEO	C0G, NP0	1.70
1	C22	470nF Capacitor	CC0603KRX7R7BB474	0603	16V	470nF	10%	Ceramic	YAGEO	X7R	2.80
3	C23, C35, C42	3pF Capacitor	GJM1555C1H3R0WB01D	0402	50V	3pF	0.05pF	Ceramic	Murata Electronics	C0G, NP0	3.85
1	C24	47nF Capacitor	GRM155C71H473KE19D	0402	50V	47nF	10%	Ceramic	Murata Electronics	X7S	1.48
3	C25, C27, C41	68pF Capacitor	GRM1885C2A680JA01D	0603	100V	68pF	5%	Ceramic	Murata Electronics	C0G, NP0	1.62
3	C26, C28, C33	33pF Capacitor	GJM1555C1H330GB01D	0402	50V	33pF	2%	Ceramic	Murata Electronics	C0G, NP0	3.11
2	C29, C36	10pF Capacitor	GJM1555C1H100FB01D	0402	50V	10pF	1%	Ceramic	Murata Electronics	C0G, NP0	3.55
2	C30, C37	1nF Capacitor	CL10B102KB8WPJC	0603	50V	1nF	10%	Ceramic	Samsung Electro-Mechanics	X7R	1.63
1	C31	0.7pF Capacitor	GRM1885C1HR70BA01D	0603	50V	0.7pF	0.1pF	Ceramic	Murata Electronics	C0G/NP0	2.06
1	C32	8pF Capacitor	0603N8R0D500CT	0603	50V	8pF	0.5pF	Ceramic	Walsin Technology Corporation	C0G, NP0	1.48
4	C38, C43, C44, C45	6.8pF Capacitor	GRM1555C1H6R8BA01J	0402	50V	6.8pF	0.1pF	Ceramic	Murata Electronics	C0G, NP0	1.48
1	C39	4.7pF Capacitor	GJM1555C1H4R7WB01D	0402	50V	4.7pF	0.05pF	Ceramic	Murata Electronics	C0G, NP0	3.85
1	C40	1pF Capacitor	GRM1885C1H1R0WA01D	0603	50V	1pF	0.05pF	Ceramic	Murata Electronics	C0G, NP0	3.24

G.1.3. Inductors

QTY	Designator	Description	Part No.	Package	Value	Tolerance	Type	Material - Core	Manufacturer	Current Rating	Price (ZAR)
1	L1	15uH Inductor	MLZ2012N150LTD25	0805	15uH	20%	Multilayer	Ferrite	TDK Corporation	250mA	2.65
1	L2	Ferrite Bead Inductor	PBY160808T-601Y-N	0603	600R @ 100MHz		Ferrite Bead		YAGEO	1A	1.48
1	L3	47nH Inductor	LQW15AN47NG00	0402	47nH	2%	Wirewound	Non-Magnetic	Murata Electronics	210mA	2.66
1	L5	2.6nH Inductor	LQW15AN2N6B80D	0402	2.6nH	0.1nH	Wirewound		Murata Electronics	1950mA	4.92
1	L6	10nH Inductor	LQW18AN10NG8ZD	0603	10nH	2%	Wirewound	Non-Magnetic	Murata Electronics	1.6A	4.42
1	L7	11nH Inductor	LQW15AN11NG80D	0402	11nH	2%	Wirewound	Non-Magnetic	Murata Electronics	1.4A	3.85

G.1.4. Resistors

QTY	Designator	Description	Part No.	Package	Value	Tolerance	Power Rating	Manufacturer	Composition	Price (ZAR)
1	R1	2K Resistor	RMCF0805JT2K00	0805	2K	5%	0.125W	Stackpole Electronics Inc	Thick Film	1.47
1	R2	470R Resistor	CRGCQ0805J470R	0805	470R	5%	0.125W	TE Connectivity Passive Product	Thick Film	1.47
3	R3, R5, R6	200R Resistor	RR0816P-201-D	0603	200R	0.5%	0.063	Susumu	Thin Film	1.47
2	R4, R7	1K Resistor	CPF0603F1K0C1	0603	1K	1%	0.063W	TE Connectivity Passive Product	Thin Film	2.80
3	R8, R9, R10	110R Resistor	RR0816P-111-D	0603	110R	0.5%	0.063	Susumu	Thin Film	1.47
1	R11	10K Resistor	RC0603FR-0710KL	0603	10K	1%	0.1W	YAGEO	Thick Film	1.48
2	R12, R13	100R Resistor	RC0402FR-07100RL	0402	100R	1%	0.063W	YAGEO	Thick Film	1.48

G.2. Base Station

Qty	Designator	Description	Manufacturer	Part No.	Price (ZAR)
1	AN1	SMA Connector	Linx Technologies In	CONSMA001-C-G	0
1	AN2	RF Antenna	Abracon LLC	AEACAC053010-S868	89.84
1	C1	10uF Capacitor			0
1	U1	LoRa Transceiver Module	RF Solutions	RFM95W-868	112.70
1	U2	40-pin Female Header			0
1	U3	Raspberry Pi 3 Model B+	Raspberry Pi	Raspberry Pi 3 Model B+	895.76

Appendix H

Budget and Expenses

Date	Order	Decription	Amount
03-Sep	Order 10082	Field Device, Debugger	-2174.82
10-Sep	Order 10112	LoRa Module	-207.84
11-Sep	Cash Sale	SD Card - Incredible Connection	-69.00
14-Sep	Order 10127	RF Antenna	-89.84
21-Sep	Order 10156	Raspberry Pi 3 Model B+	-741.35
22-Sep	Order 10082	Batteries - Out of Stock (cancelled)	293.98
27-Sep	Order 10082	Inductors - Out of Stock (cancelled)	5.30
	Order 10177	Inductors - 15uH - Replacement	-5.30
04-Oct	Order 10082	RGB LED - Out of Stock (cancelled)	18.06
	Order 10214	RGB LED - Replacement	-9.06
12-Oct	Cash Sale	RFM95W - LoRa Module - MicroRobotics	-112.70
13-Oct	Cash Sale	JST Kit - Solar Panel Connector - MicroRobotics	-10.35
		Total Expendature	**-3102.92**

Appendix I

Photos of Devices and Implementation

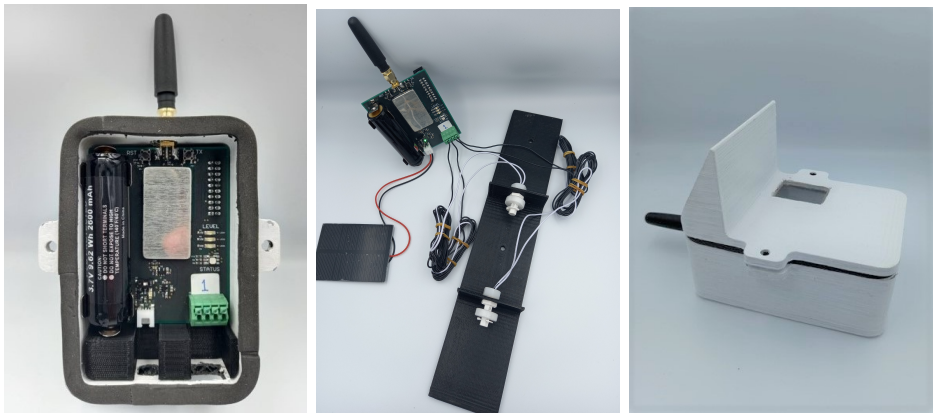
I.1. Field Device and Base Station

I.1.1. Field Devices

PCBs before Populating

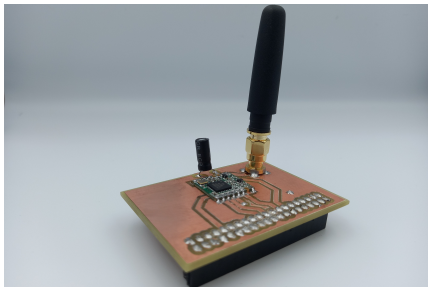
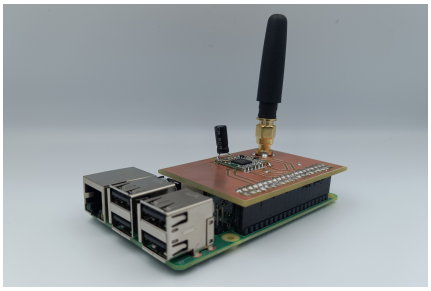
Assembled Devices

Field Device with Enclosure and Accessories

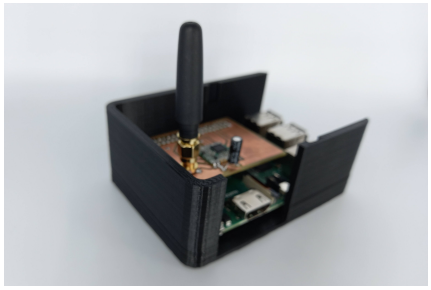


I.1.2. Base Station

HAT

Base Station with Enclosure



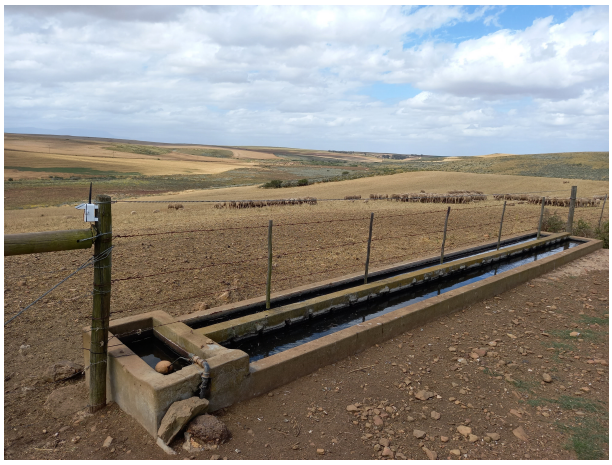
I.2. Devices used during Solution Development

Nucleo Board

ST-Link/V2

I.3. Implementation

Trough-1



Trough-2

Base Station

Appendix J

Version Control

Version control was done using OneDrive and GitHub. The following GitHub repositories are private. Access can be requested by sending an email to 21574081@sun.ac.za.

Nucleo Board Software	https://github.com/21574081/Skripsie_NucleoBoard
Field Device Software	https://github.com/21574081/Skripsie_FieldDevice
Base Station Software	https://github.com/21574081/Skripsie_Dashboard
Schematic and PCB Designs	https://github.com/21574081/Skripsie_AltiumDesigner