FINAL REPORT: ICE-THICKNESS MAPPING USING A DRONE-MOUNTED GPR SENSOR PACKAGE

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1. Executive Summary

The drone-mounted ground-penetrating-radar (GPR) sensor package project was a partnership between Ocean Networks Canada (ONC) and an ECE 399 design group. This project consisted of developing a GPR sensor package that could be mounted to an over-the-shelf (OTS) fixed-wing drone to measure the thickness of ice quickly, simply, and efficiently for commercial ship industries operating in arctic climates. This report outlines the research, findings, and difficulties that were discovered during the completion of the sensor package design project.

The GPR sensor package consists of a GPR, communication, microcontroller, and power module that will be securely mounted in the weather-proof case. The sensor package will be mounted to an OTS fixed-wing drone to allow for rapid testing of large areas of ice. GPR was chosen for this design due to its efficiency, accuracy, and relative simplicity. The communication module was included to transfer real-time data and instructions between the ground control unit (GCU) and the sensor package to control the movement and operation of the drone and sensor package as well as transfer measurement data back to the GCU. The Atmel SAMV71 was chosen as the MCU of the sensor package as its speed and precision can match the design requirements set in the design process. The sensor package is designed to consume minimal power and thus can be powered by lightweight 18650 lithium-ion batteries which allow for a significant operational time of 5.2 hours.

This drone-mounted GPR sensor package design solution achieves all of the design requirements set during the design process and thus is feasible. The next steps of the design process consist of procuring funding and materials to construct a functional prototype for testing. The testing should be completed in a simulated or actual arctic climate to ensure the proper operation of the prototype.

2. Introduction

ONC is interested in the research and development of ice-thickness mapping technology that can be deployed using drone/UAV systems. As part of UVIC's ECE 399 course, the GPR sensor package will be designed to integrate with certain OTS drones to transfer real-time ice-thickness measurements to the ground control unit. This document will cover the project scope, literature review, proposed design, and evaluation of the design.

2.1. Stakeholder Perspective

Ocean Networks Canada operates advanced observatories that collect data on physical, chemical, biological, and geological aspects of the ocean to advance the research of complex Earth processes. The need for this project originates from ONC's interest in developing easier methods to measure the thickness of ice. The current ice-thickness measuring solutions consist of using radar sensors that are mounted in manned aircraft or dragged behind surface vehicles. However, these solutions are impractical and inefficient for commercial shipping and tourism applications. The drone-mounted GPR sensor package would provide an efficient and simple way for ONC and commercial industries to measure ice-thickness as they travel through the Arctic Ocean.

2.2. Product Functional Requirements

The main requirements for the drone-mounted ice-thickness measuring GPR sensor package are:

- The GPR is capable of measuring ice-thickness of 10 m at more than 10 m above the ground.
- The data resolution of the GPR system has a precision of +\- 15 cm.
- The sensor package has dimensions of at most 15 cm x 15 cm x 10 cm and weighs less than 1 kg.
- The sensor package can communicate with the ground control unit for data transfer.
- The power consumption of the sensor package is between 250 mW and 5 W.
- The drone and sensor system operates at a velocity of 7 m/s or higher.
- The sensor package functions in sub-zero temperatures, high winds, and snow/rain.

3. Project Scope

The problem statement, assumptions, and constraints that defined this project's design process are described throughout this section.

3.1. Problem Statement

ONC needs an efficient drone-mounted ice-thickness measuring sensor to overcome the problems that face the current ice-thickness measuring solutions. This technology would benefit commercial ship industries operating in northern climates as well as northern communities. This need shaped the design process of our efficient and simple drone-mounted GPR sensor package.

3.2. Assumptions

The assumptions that were made to limit the scope of the drone-mounted GPR sensor package project are:

- An independent drone system capable of carrying the package is available.
- The fixed-wing drone has autonomous flight capabilities.
- An external computer system is available to analyze the ice-thickness data.
- An existing drone mission control software is available.
- A base station with radio communication and data processing capability is available.

3.3. Constraints

The constraints that the design process of the drone-mounted GPR sensor package project had to adhere to are:

- The sensor package will need to be securely mounted to a compatible OTS fixed-wing drone that will be launched from a ship.
- A Raspberry Pi will be used as the microcontroller. The design is constrained by the hardware of this device such as the amount of RAM and its power requirements.
- External software compatibility will limit us to certain drone mission control softwares. Our internal drone commands must be able to communicate with the drone's control software.
- The ground control unit (GCU) will have to have sufficient signal processing equipment and antenna gain.

4. Literature Review

Several methods of ice-thickness mapping currently exist such as satellite mapping, surface vehicle mapping, and airborne mapping. This project focuses on airborne mapping using a drone and the goal of the literature review is to compare the limitations of airborne measurement methods and choose the best drone deployable solution.

4.1. Radar Sounding Systems

Ground Penetrating Radar (GPR) was identified as the only viable option considering the deployment method of this project. The performance of GPR systems such as High-Frequency Sounding and using

GPR with Synthetic Aperture Radar from several studies were compared. The determination of the most suitable radar sounding system was based on two studies where a radar sensor package was deployed on a drone; “A drone carried multichannel Synthetic Aperture Radar for advanced buried object detection,” [1] from researchers at the German Aerospace Center, and “HF/VHF Radar Sounding of Ice from Manned and Unmanned Airborne Platforms,” [2] from researchers at the University of Kansas. The system developed in the first study had a penetration depth of 15m and a 250g payload. The second system had a penetration depth of 100m and weighed 3kg. These studies showed that accurate measurements with a small UAV-deployed GPR package were possible.

4.2. Drone Types

Two types of drones were considered for this project. Several factors such as carry weight, range, and battery life went into deciding the most suitable drone to carry the sensing package. The first option is multi-rotor drones. These drones allow for easy vertical take-offs and high maneuverability, but they are not fast and cannot cover a large range with any kind of payload. The second option is fixed-wing drones. These drones are often larger, more stable, and can fly further and faster. They allow for more carry weight, but they are more difficult to control and launch. The fixed-wing drone was chosen as it has better range, carrying capacity, and stability which are requirements to get suitable measurement data.

5. Proposed Design

The proposed design consists of a GPR sensor package, drone system, and base control unit.

5.1. GPR Sensor Package System Description

The drone-mounted GPR sensor package will work in tandem with the drone and the base control unit to actively scan ice thickness. The sensor package directs the drone using instructions from the GCU. It then detects the ice thickness using a GPR system and records the data. Finally, it transmits the data to the central base unit for processing. This design only includes the GPR sensor package. The fixed-wing drone and GCU are outside of the scope of this design and must be acquired separately.

5.1.1. GPR Sensor Package Module Descriptions

The three components of the proposed GPR sensor package design are the base control, drone system, and radar package. These are shown in Figure 1 of Appendix B**.**

The radar package is the primary focus of this design. Other components can be purchased OTS. The radar package has several modules described in Table 1.

Table 1: Components of the GPR Sensor Package

Module	**Description**
GPR/Antenna	Ground penetrating radar used to detect ice thickness
GPS	Global positioning device used to geotag ice thickness data
Battery	The main power supply of the radar package
MCU	An Atmel SAMV71 purposed with managing all onboard operations
Onboard Storage	A memory device used to save GPR data when communications are lost
Ports	External port used to manually access and upload data to the system
Radio Communication	A communications array is used to communicate with the drone and base unit.

5.1.2. Functional Operation Procedure

The functional operation procedure of the GRP sensor package has three stages: Take off and travel to the target location, scan the ice-thickness along the route, and return to the base for recharge. A flow chart showing the operation and scanning procedure is shown in Figure 2 of Appendix B.

5.2. Ground Penetrating Radar Module

To reduce hardware costs and performance requirements, a pulse GPR using an equivalent sampling technique will be used.

5.2.1. GPR Module Design

The MCU triggers a timing controller which initiates a GPR pulse and starts a timing circuit to capture the response. After a few ns delay, a sample is received by the RX antenna and amplified for the sampler. This data is collected by an ADC and sent to the MCU for geo-tagging and processing. The component design of the GPR module is shown in Figure 3 in Appendix B.

Two custom circuits are required for this implementation: an equivalent sampling circuit and a sampling pulse generator circuit. These designs are shown in Figures 4 and 5. Other components such as amplifiers and timing modules can be purchased. Potentially viable components are shown in Table 2.

Table 2: GPR Module Components

Module	**Component**
Rx Low Noise Amplifier	PMA3-83LN+ [4]
Precision Timing module	SY89297U [5]
Tx High Power Amplifier	HMC311ST98E [6]

5.3. Radio Communications

The drone flight controller, sensor package, and ground control unit (GCU) will be linked through radio and serial wired connections. The drone flight controller will be linked to the sensor package via USB or other wired serial connection. This will allow the control signals for the drone to be received from the sensor package. The sensor package radio module will be receiving these control signals from the GCU via a 433MHz comms link as seen in Figure 6. The data link will pass through the same 433MHz communications link. This allows for constant control of the drone with no data interruptions. The radio module interface will be made up of the Tx/Rx for the control link and a single Tx antenna for data uplink. The TEL0116 radio module chosen has parameters provided in Table 3. The radio module will be connected using the UART communication protocol.

Table 3: Communication Module Parameters

Parameter	**Range**
Output power:	≤ 20dBm
Receiving sensitivity:	-148dBm
Serial baud rate	1200 ~ 57600,9600bps (default)

The radio module chosen for the sensor package is a TEL0116. This module allows for a 433Mhz LoRaWAN communication link. The Long Range Low Power Transceiver chip used in the TEL0116 radio module is an SX1278. The SX1278 is a half-duplex, low-IF transceiver. The chip has a pair of ADCs that can perform the needed data conversion as seen in Figure 7. The frequency synthesizers generate the local oscillator frequency for both receiver and transmitter, one for the lower UHF bands up to 525 MHz, and the other for the upper UHF bands from 779 MHz [7]. The RF power amplifiers can deliver up to +14 dBm and can deliver up to +20 dBm via a dedicated matching network. The receiver has a sensitivity from -111dB to -148dB with an effective bit rate of .018 - 37.5 kbps at a bandwidth of 7.8 - 500 kHz. The SX1278 incorporates the LoRa spread spectrum modem which can achieve a longer range based on FSK or OOK modulation. The module allows for FSK, GFSK, MSK, GMSK, LoRa and OOK modulation making it versatile for a communications processor.

The range of the system depends on the antenna gain and frequency chosen for the radio link. The frequency chosen for communications is 433MHz. As seen in Figure 8 the path loss at 100km is still within the receiver sensitivity for signal detection using an omnidirectional antenna. The omnidirectional antenna can also be seen in Figure 9. which shows the radiation pattern for the antenna. The antenna allows for gain at all angles. With constant Line-of-Sight and considering clear skies, a communications distance of +100km can be achieved.

5.4. Serial Connections

The connections between modules will use the Serial Peripheral Interface (SPI) for synchronous serial connection. SPI allows for full duplex communications compared to IC2 half duplex. SPI data rate is 10Mb/s between modules due to the full duplex communication. The sensor package MCU is the SPI master and all connecting modules become slave devices without adding any slave select. All connecting modules using SPI can be seen in Figure 10. The storage module is a Micro SD Card Adapter Module; it can accept any microSD card. The GPS module will be a Grove-GPS (Air530) which provides high-accuracy GPS coordinates [8].

External data from the drone flight controller will be retrieved through a USB connection. The drone flight controller will provide the sensor package with redundant GPS coordinates and drone flight telemetry data such as axis angle, speed, and altitude.

6. Evaluation

6.1. GPR Sensor Package

The novel components of the sensor package including the airborne GPR, signal processing method, GPS positioning, and communication equipment combined with a battery-powered system require a feasibility evaluation. Other components are commonly implemented in the manner described.

The GPR device has the highest power and performance requirements of the system. However, based on other implementations, the expected power draw of the GPR is between 250mW and 10W [1][2]. The selected battery can easily supply this for an extended period. In terms of performance, with the requirements of a 10 m penetration depth with a precision of +/-15cm, a pulse GPR system requires parameters as shown in Table 4. These can easily be achieved with the selected hardware and common electronic devices.

Table 4: GPR System Parameters

Requirement	Value	Relevant Parameter	Value
Penetration Depth	> 10 m	Minimum Pulse Repetition Interval	500 ns
Resolution	< 15 cm	Pulse Width	1 ns

Regarding obtaining GPR sample acquisition by an ADC, using the equivalent sampling technique allows for slower hardware to manage the digitization of the data. Should a single ADC be unable to keep up with the sampling timing, a MUX system with multiple ADC and a sample hold system can be easily implemented on most MCUs. Thus, data acquisition of the GPR data will be feasible.

The geo-tagging of GPR samples may be difficult in some arctic locations due to GPS dead zones. However, should such a situation arise, other instrumentation such as compass and accelerometer readings can be used to approximate the direction and area of the scan. In addition to the accuracy of the GPS coordinates, GPS data from the drone controller can be compared for further reference. In this case, certain errors may be present, but a general sense of the ice thickness of the region may be obtained.

With the low-flying nature of this drone, communication requires line of sight may not always be possible. Consequently, the sensor package is also equipped with onboard storage to enable data to be saved rather than transmitted. With this hardware, a drone may finish its path sweep before flying to the communication zone and transmitting the GPR and GPS data.

The above analysis provides strong evidence that the design system will be feasible. The limitations of this system are:

- The range will be limited to under 100km based on the power required by the drone and GPR system.
- GPS positioning may lack precision in certain regions of the Arctic due to satellite unavailability.
- Inclement weather in certain situations can render the drone unable to communicate with the GCU.

6.2. Microcontroller

The Atmel SAMV71 microcontroller was selected based on the scanning speed and precision requirements. The microcontroller provides a conversion rate of 2 MHz which is sufficient to read every 500ns from the ADC as per accuracy requirements [11]. The maximum speed of the microcontroller is 300 MHz which allows it to process the data every 500ns [12]. These fit the design requirements for the MCU.

6.3. Battery and Power

The sensor package power will be provided by 3 parallel Samsung 30Q 18650 lithium batteries [10]. The overall power consumption of the GPR system will be around 250 mW - 5 W. Three 18650 battery cells can provide a total of 9000mAh which can enable a GPR operating time of 5.17 hours at 3.6V. Once again attaining the design requirements.

7. Drone Flight Regulations

Transport Canada has been conducting drone trials in the Canadian Arctic for the last few years [13]. These trials help the government to develop procedures, training, and risk assessment tools for safely operating drones in the Arctic. More regulations are expected in the future as drone usage in the Arctic grows.

In Canada, 3 certifications are required to operate the ice-measuring drone system in the Arctic. Special Flight Operations Certificate (SFOC) is required for operating a drone beyond a visual line of sight. It may take 30-60 days to review and issue the certificate. A valid drone pilot license and drone registration are required to operate a drone that is more than 250 grams [14]. As each country has different legal requirements for drone operations, regulations for different countries must be reviewed.

8. Social Implications

Even though the ice-measuring drone system covers large areas and costs less to operate than any other method of gathering data, there are social and ethical implications that should be considered.

Privacy issues could arise as the drone has a camera that could potentially take a video of a passing ship while collecting the data. Also, an encounter between a drone and a bird is possible which could lead to physical injuries of a bird. In some cases, drones are attacked by birds as they are perceived as a threat [15]. After the attack, there is a high chance of the drone crashing and getting lost in the Arctic, if not found. If a drone's battery is mechanically damaged, corrosive fluids can start leaking and polluting the waters. As most drones are made of metal and plastic, it would take several decades to decompose [16].

9. Conclusion

A design for an ice-thickness measuring sensor package was proposed and evaluated. Several systems that make up the sensor package are GPR, microcontroller, communication module and the battery power system. Each system was evaluated against the defined requirement specifications and components were chosen accordingly.

Future work includes designing and manufacturing PCB circuits. Once the manufacturing is complete, the sensor package should be tested with third-party GPR analysis software. Ultimately, further testing and design are required to develop the ice-thickness measuring sensor package, however, the design solution proposed is feasible.

10. References

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Appendix A: Glossary

The following terms were used throughout the report.

Term	Description
ONC	Ocean Networks Canada
UAV	Unmanned Aerial Vehicle
OTS	Over-the-Shelf
MCU	Microcontroller Unit
RAM	Random Access Memory
ADC	Analog-to-digital converter
GCU	Ground Control Unit
GPR	Ground Penetrating Radar

Appendix B: Proposed Design Figures

The diagrams that were discussed in the Proposed Design section have been included in this appendix.

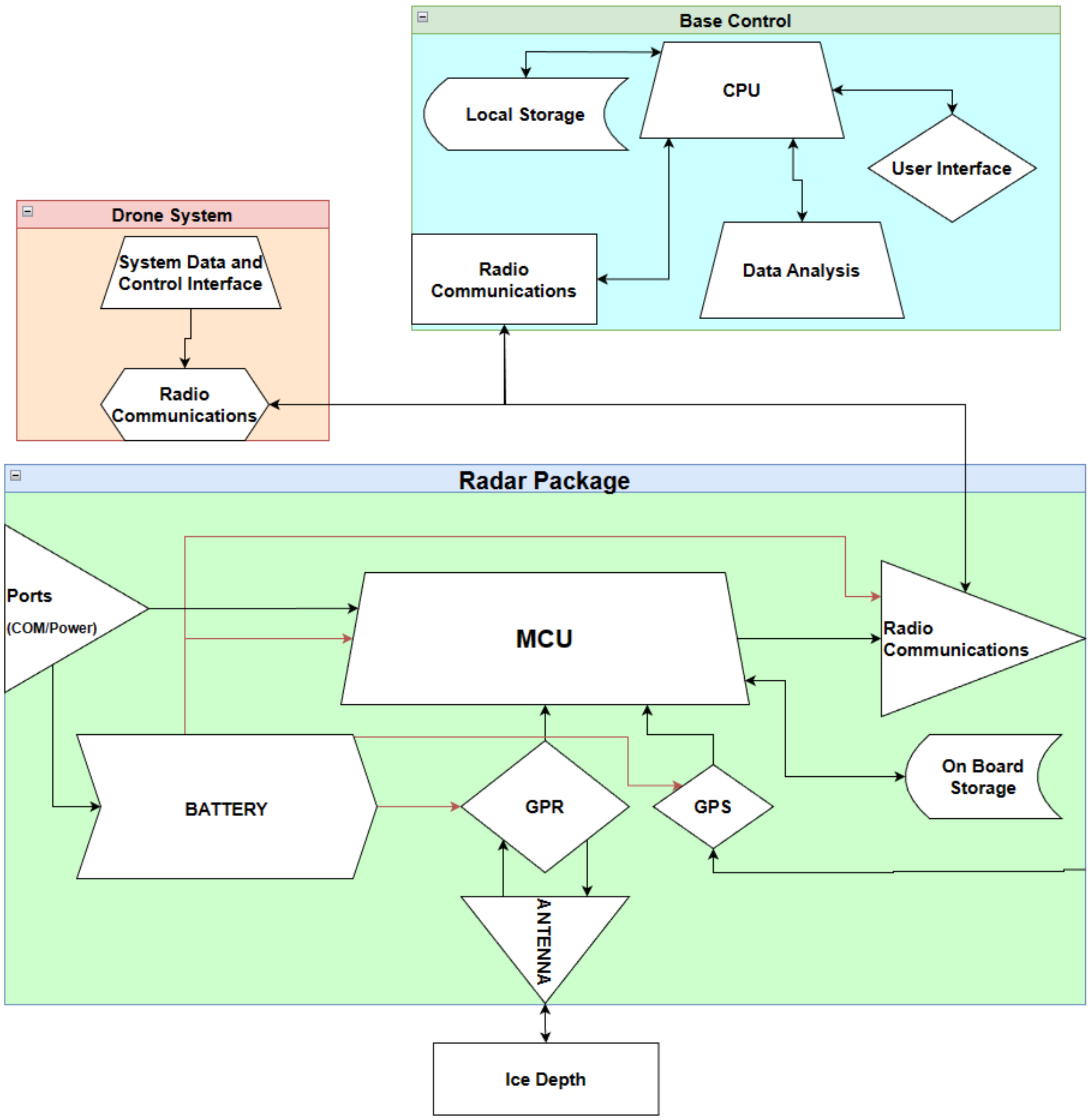

Figure 1: GPR Sensor Package Subsystem Diagram

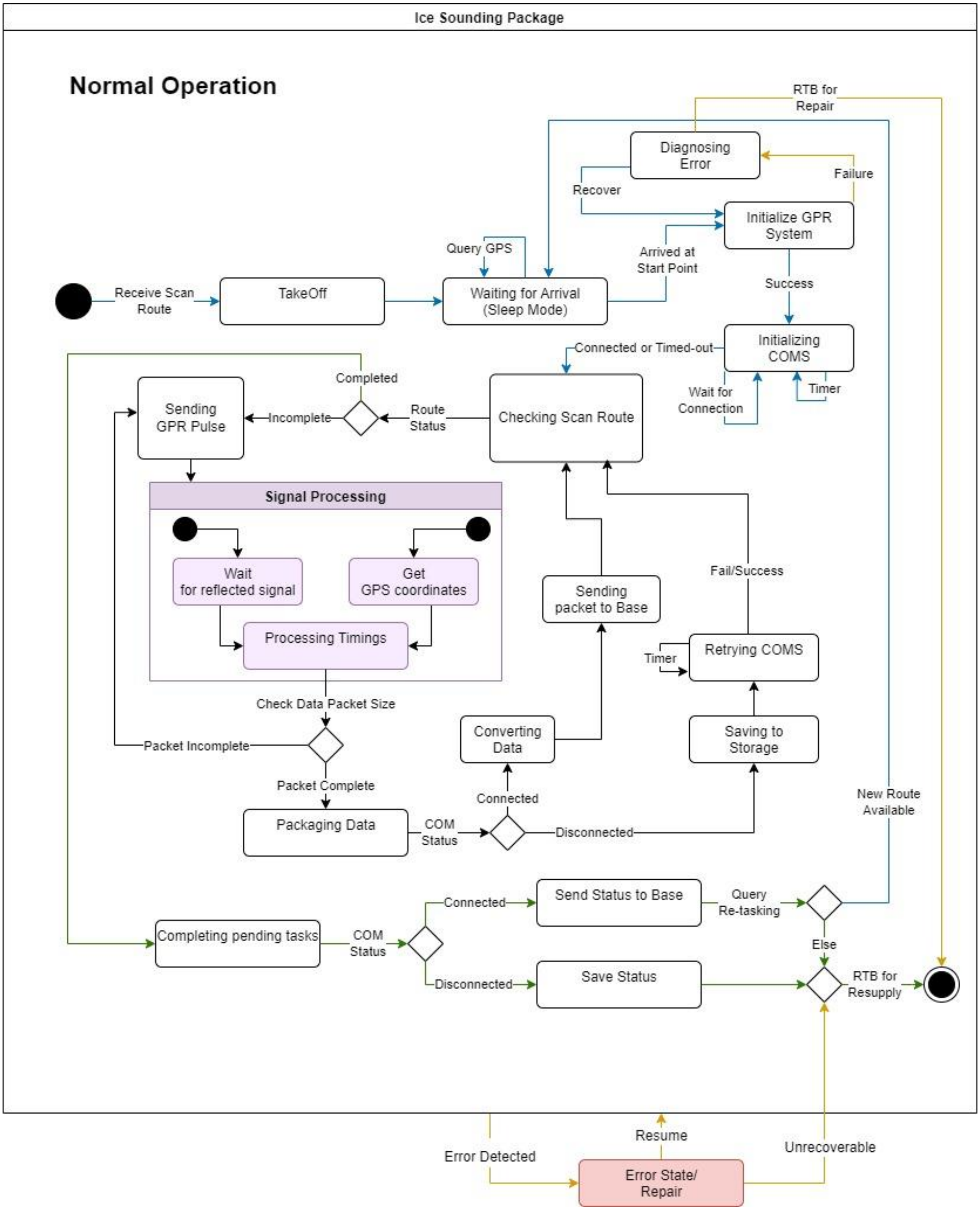

Figure 2: Functional Operation of Sensor Package Flowgraph

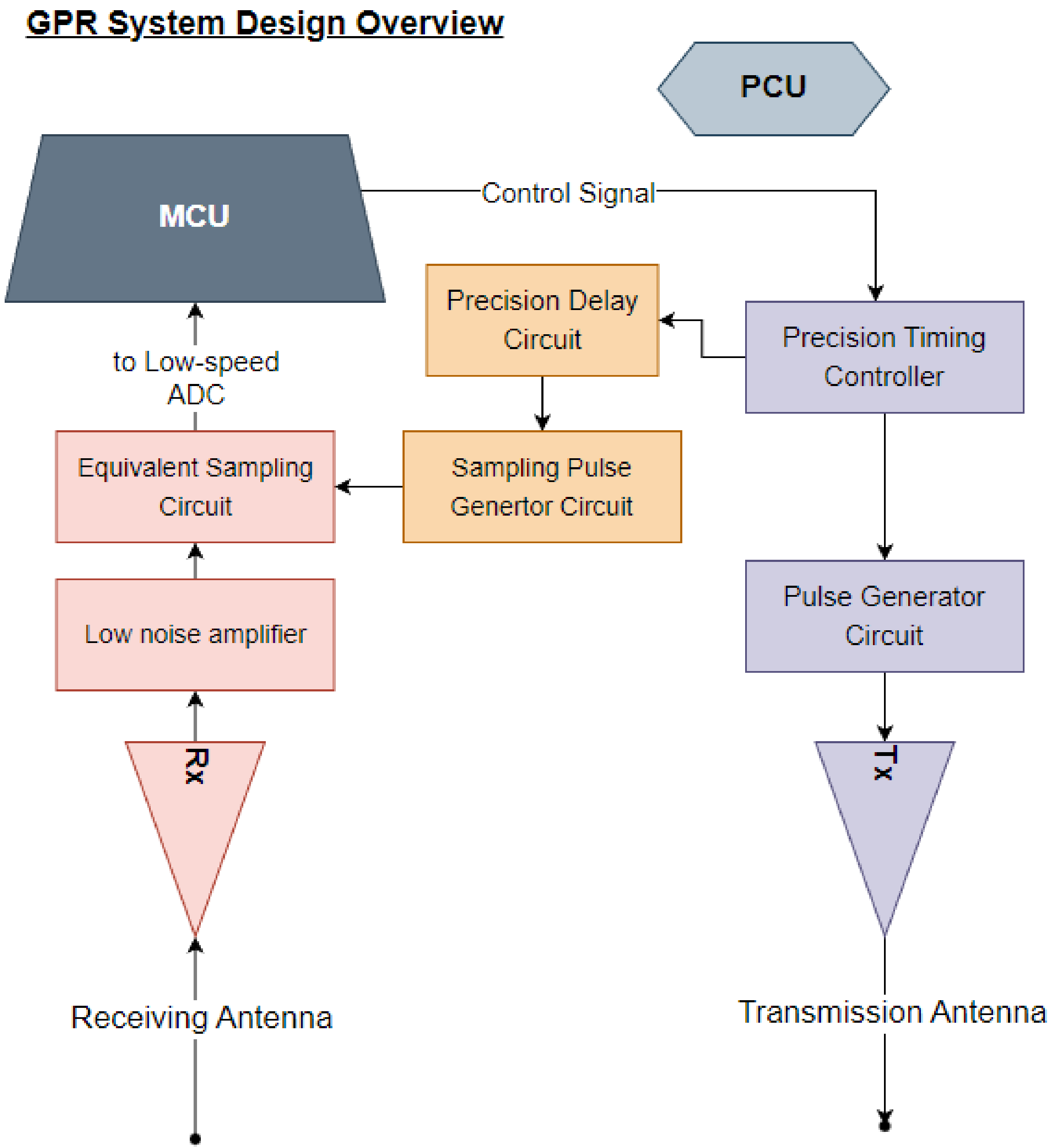

Figure 3: Component Design of GPR Module

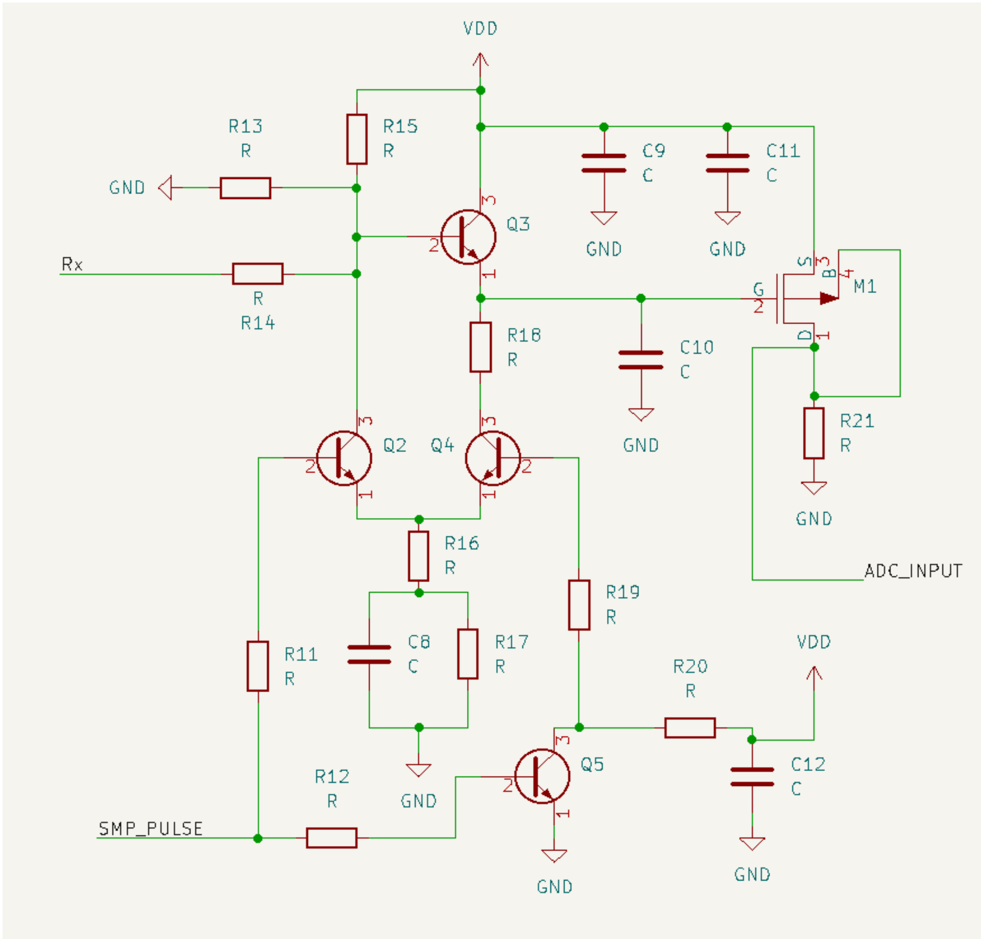

Figure 4: Equivalent Sampling Circuit [3]

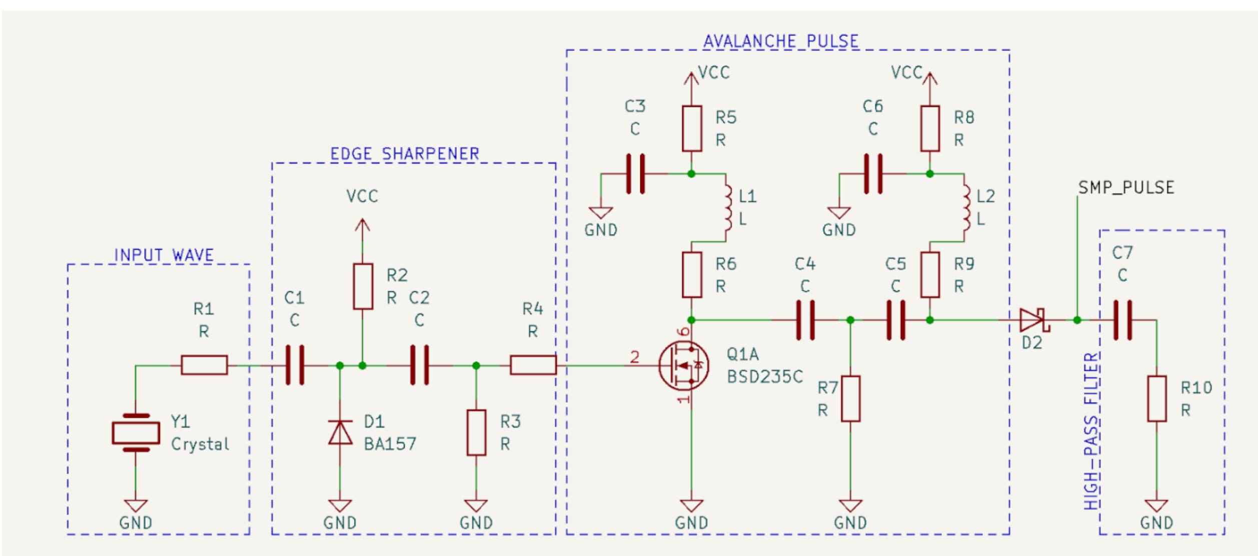

Figure 5: Pulse Generator Circuit [3]]

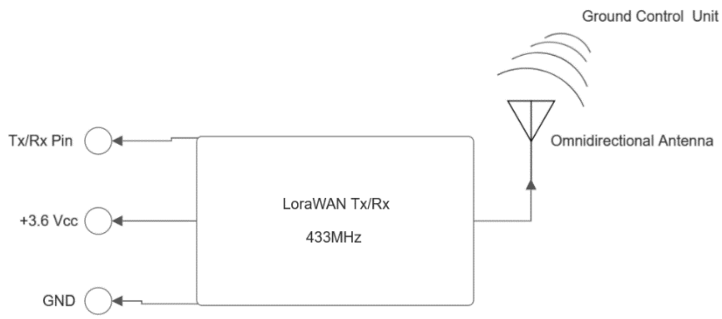

Figure 6: Data Link from Radio Module to GCU

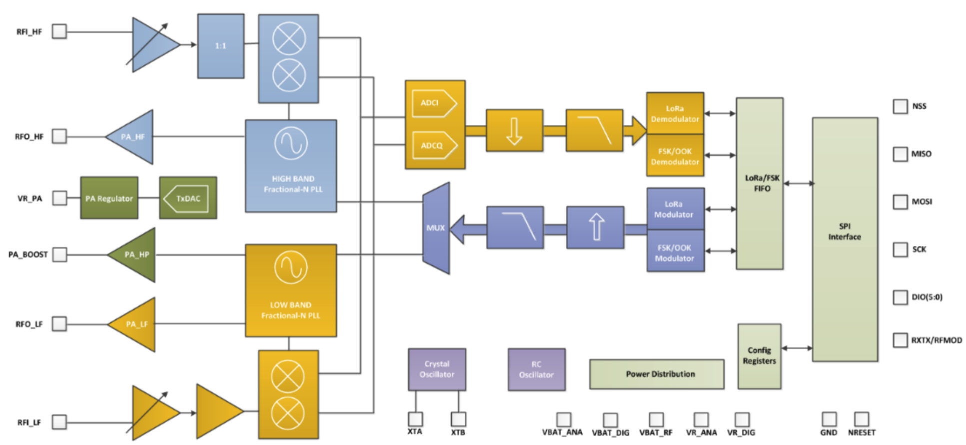

Figure 7: SX1278 Block Diagram

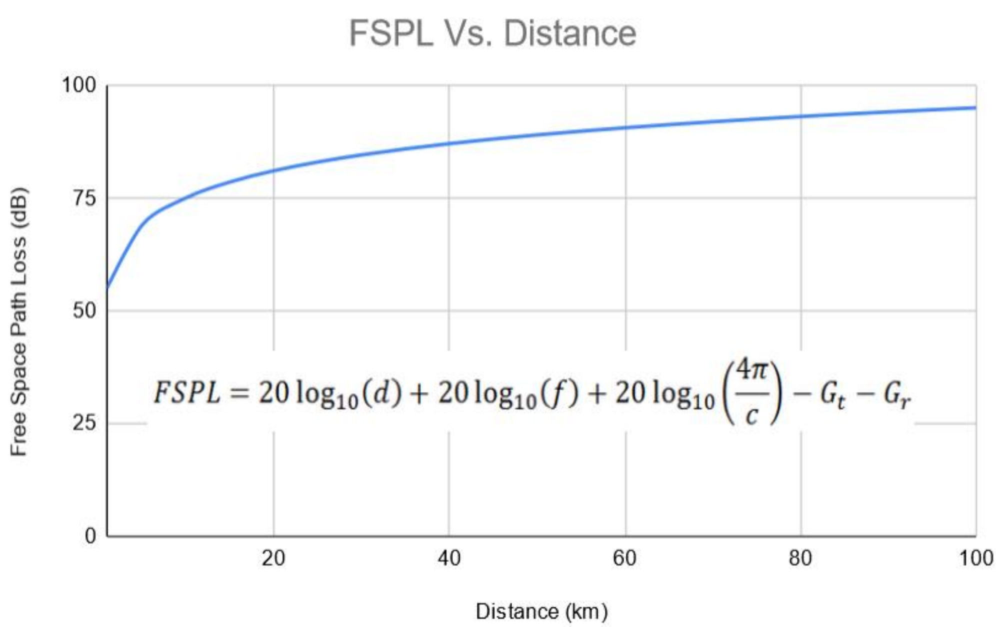

Figure 8: Pathloss vs. Distance for 433 MHz Using Omnidirectional Antenna

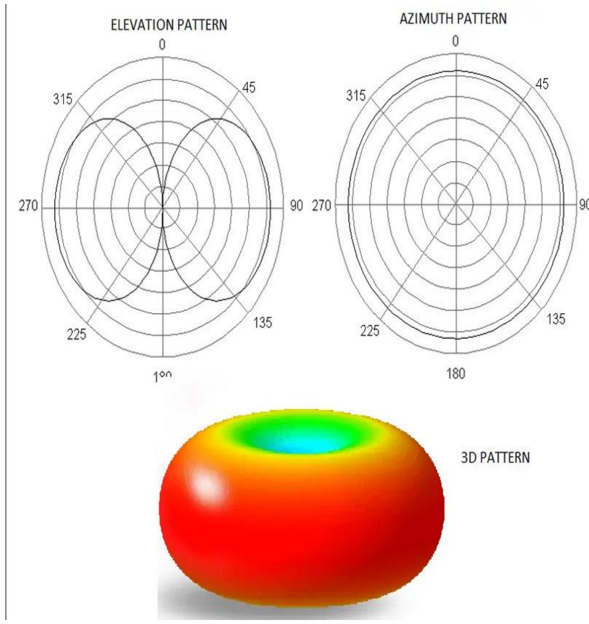

Figure 9: Omnidirectional Antenna Pattern

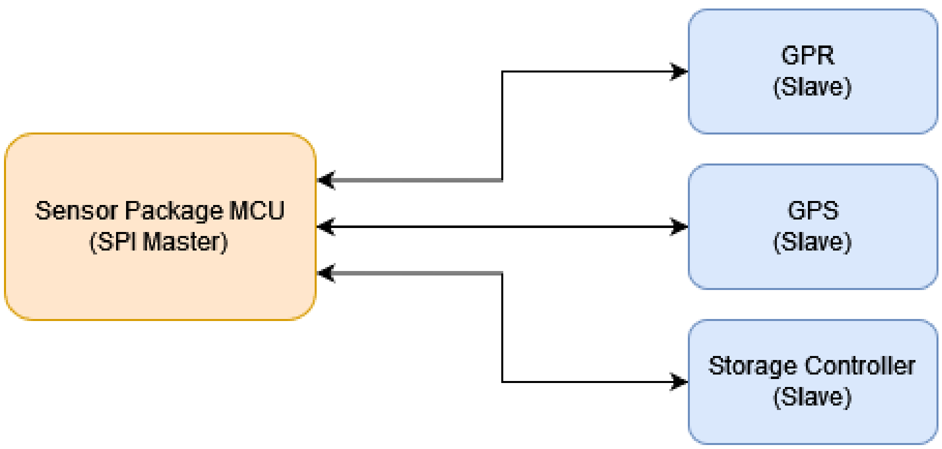

Figure 10: SPI Connection Diagram