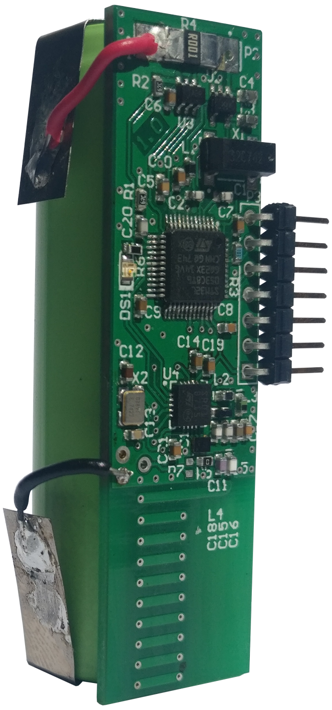

DEVELOPMENT OF A WIRELESS CELL BASED BATTERY MANAGEMENT MODULE

Master's thesis in Embedded Electronic System Design

FREDRIK BJERSING and RASMUS DAMBERG

Department of Computer Science and Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
UNIVERSITY OF GOTHENBURG
Gothenburg, Sweden 2018

MASTER'S THESIS 2018

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Cover: A working prototype of the developed battery management system

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Abstract

This report describes the design and development of a wireless cell based battery management module. The module should be able to accurately measure the battery voltage, current and temperature and then transmit this information wirelessly to a receiver. The system should have a low power consumption both when the monitored battery is used and when it is not. At least 40 systems should be able to communicate simultaneously.

The design does current measurements through a shunt resistor, voltage measurements using a voltage divider and an Analog to Digital Converter(ADC) and temperature measuring using the microcontrollers own sensor. Wireless transmission is achieved by a SPIRIT1 radio chip combined with an antenna and is broadcasted on the 868 MHz radio band using a custom designed protocol.

The system can perform all the desired measurements, with generally high accuracy. An issue with the antenna prevents long range communication and multiple units, but tests indicate that the wireless communication concept is feasible for at least 40 units. The power consumed is not a significant part of the total battery capacity when in use, but drains the battery relatively quickly when not in use.

Keywords: BMS, Battery Management System, 868 MHz, Low Power, Distributed, Wireless

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FREDRIK BJERSING and RASMUS DAMBERG, Gothenburg, May 2018

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1
Introduction

Battery management technology is a major field within today's industry. Batteries are used in an ever increasing scale in electronic products and their lifetime depends highly on their usage, making battery management more necessary than ever. Different topologies of Battery Management Systems (BMS) exist; such as centralized, distributed and modular. Centralized means that a central unit is doing all the measuring and processing on its own. A modular system contains several smaller systems that each handles a portion of the batteries. Finally, a distributed system contains many measuring units that all report the measurements to a central unit that handles the processing [1].

This thesis work focuses on a wireless distributed BMS. Although distributed systems are associated with their own set of problems, such as high cost and space overhead, they also have a great potential for some desirable features such as safety, reliability, scalability and simplicity. Through wireless communication between the measuring units and the central unit, the reliability could be even higher, while also potentially reducing the total weight and size of the BMS. These properties would make such a system desirable in applications where either size or weight are important properties. While significant studies in the subject of BMS have already been made [2] [3], further research on distributed systems, especially with wireless communication, is necessary .

1.1 Background

Today, everything from phones and laptops to bikes, drones and even cars are powered by electricity in an ever increasing rate. Naturally, batteries are used in most of these applications in order to supply the necessary power. With the limited advances in battery technology, focus is instead put on optimizing the current battery setups to fully utilize them, increasing the battery lifetime.

To be able to utilize the batteries fully and to predict when they will be fully discharged, more information about them must be continuously acquired. In applications where the battery is drained in a slow and predictable way, the voltage level usually is a good indicator on battery charge levels. When the discharging is unpredictable and produces a high current, the voltage no longer represents the charge level adequately, making other ways to keep track of charge levels necessary [4]. This leads to the introduction of more complex BMS that monitors different battery properties. A wide range of different properties can be monitored, but in general at least voltage, current and temperature are measured. Through these parameters it is possible to determine the status of the battery, both in terms of remaining charge and battery health. Based on this information, suitable actions can then be taken, such as balancing uneven voltages, replacing faulty batteries or cooling the batteries [1].

Traditional distributed BMS uses wires to connect all the sensors and usually group several battery cells together to one battery pack, monitored by one set of sensors. With increasing battery pack sizes and requirements for reliability and precision for BMS, the measured values are sometimes not accurate enough and the wires become an issue considering size limitations, weight limitations or reliability requirements. The battery grouping also limits system modularity, since batteries now must be added or replaced in groups rather than individually. The next step for BMS is therefore systems in which each battery cell is monitored individually for increased accuracy and modularity and the information is transmitted wirelessly to avoid the fragile and heavy wiring [5].

1.2 Goal

The goal of this project is to develop and construct a distributed BMS with measurement capability applied to every individual battery cell. The system should be able to measure voltage and current with an accuracy of 10 mV and 10 mA respectively, which is enough to get a good estimation of the battery capacity. The temperature should be measured with an accuracy of 1 °C, which is within the safety margin for the battery. The measurements should be done by a measuring unit on each cell, which then should be able to transmit this information wirelessly to a central unit with an average of at least 1 reading per second. This transmission frequency is selected to match the intended applications, described in Section 1.3.

The communication should not interfere with or be interfered by other common forms of communications such as Wi-Fi networks or Bluetooth connections. In order to be a functional and usable system, power consumption for the measuring units should be below 0.7 mW each while the system is idle. This number is chosen as it gives the cells approximately two years of time when not in use before being fully discharged due to the BMS. When active, no more than 1% of the total power consumption should come from the BMS. These requirements are chosen so the design will have a limited impact on battery performance, while also allowing the battery to be stored without fully discharging for at least two years. The system should be small enough to fit the footprint of a regular Li-Ion battery cell.

1.3 Applications

The system should be designed for applications where several battery cell are combined, either in parallel, in series or both. The system is intended for applications where the current in the batteries is unpredictable and where the batteries are discharged quickly, as this makes simple voltage-based charge calculations difficult and less reliable. Applications where high performance and low weight is desired would also benefit from a system like this. Examples of applications that match these criteria are electrical bicycles and drones, as both of these draw current in a rapid and unpredictable way, while also benefiting from increased battery lifetime and reduced weight. The system can also be used in battery packs used as back-up units in for example data centers, where the wireless communication would improve modularity and potential for hot-swapping within that system.

1.4 Project questions

- Is it possible for at least 40 measuring units to communicate simultaneously without interference from other systems?
- What are the main benefits and drawbacks, compared to a commonly used commercial system, as presented in 2.2.2?
- Is it economically viable to have an individual measurement system on every single cell?
- Is it possible to construct the system so that power consumption is less than 0.7 mW per measuring unit while idle and less than 1% of total consumption when active?

1.5 Delimitations

- Only current, voltage and temperature are to be measured
- State of health or state of charge algorithms will not be implemented
- Only rechargeable lithium ion batteries are to be included
- Only wireless communication options are to be considered

1.5.1 Ethics

A more advanced BMS would allow products to fully utilize each battery cell so that no energy is wasted. More battery capacity would also mean that the capacity gap between rechargeable and non-rechargeable would be reduced, promoting the use of rechargeable batteries. This in turn would reduce the power needed for battery production as well as electronic waste and chemical use.

The wireless technology potential to reduce the products weight. This is an important factor in applications such as electric vehicles, since each weight reduction increases the range significantly. This system therefore has potential to reduce energy waste for vehicles, while the lack of cables also mean less electronic waste.

1.6 Thesis Outline

Chapter 2 explains the theory behind all the technologies and concepts related to this project. Even the solutions or concepts that were considered but did not make it to the final product are explained here.

In Chapter 3, the process for creating the product is presented. It is divided into several smaller parts for the different parts of the process. The hardware sections explains the process behind the creation of the physical product. The software section explains the process of creating the software for both the transmitters and the receiver unit. The process of testing and verifying the product is explained in the verification section.

Chapter 4 contains all the information about the finished product. Any choices with regards to technology or concepts are presented and explained here, both in regards to software and hardware. The communication strategy and protocol is also explained here.

In Chapter 5, all the measured and calculated results found in this project are presented. Properties such as sensor accuracy, power consumption and communication results can all be found here.

In Chapter 6 and Chapter 7, the results of the project are analyzed and discussed, with answers to the research questions. Features that did not work as intended or with potential to further improve the results that were discovered during the project are presented. Potential applications and uses for the system are suggested and discussed. Future concepts that have the potential to improve another iteration of the project are presented and discussed. Finally, a conclusion is presented based on the discussion on whether the concept of wireless distributed BMS is useful or not.

2
Theory

In this chapter, the theory behind every key concept of the project is explained. In cases where there are multiple different options for a choice made within the project, each relevant option is briefly explained here. It also contains some theory about batteries and other technologies and concepts related to this project.

2.1 Lithium Ion batteries

Lithium Ion (Li-Ion) is a common battery type, which since its invention in 1991 has come to be a standard among portable electronics [6]. They come in many different sizes, shapes and capacities depending on the application. The standard package is a metal cylinder with connectors at both ends. They have an operating voltage of between 4.2 V to 2.5 V, where the voltage decreases as the batteries are discharged.

Like all batteries, the voltage only depicts the charge level accurately if the battery is discharged slowly and linearly. This effect can be seen in the figures below, under a constant current discharge the voltage decreases linearly as seen in Figure 2.1. During rapid changes of load with large current swings the battery voltage does not accurate represent the level of charge left in the battery, as seen in Figure 2.2

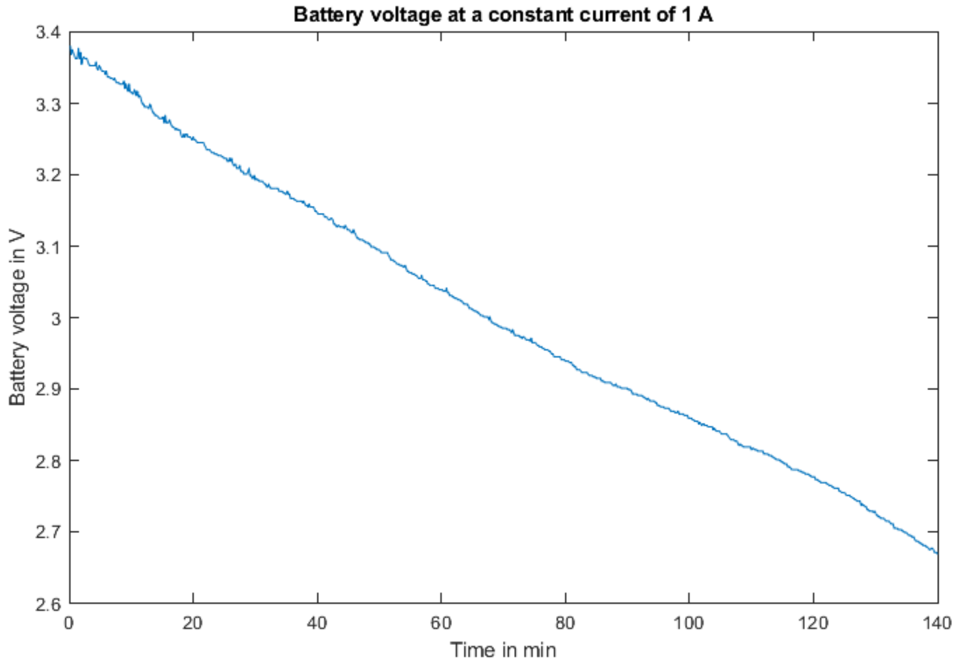

Figure 2.1: Battery voltage when discharging at 1 A

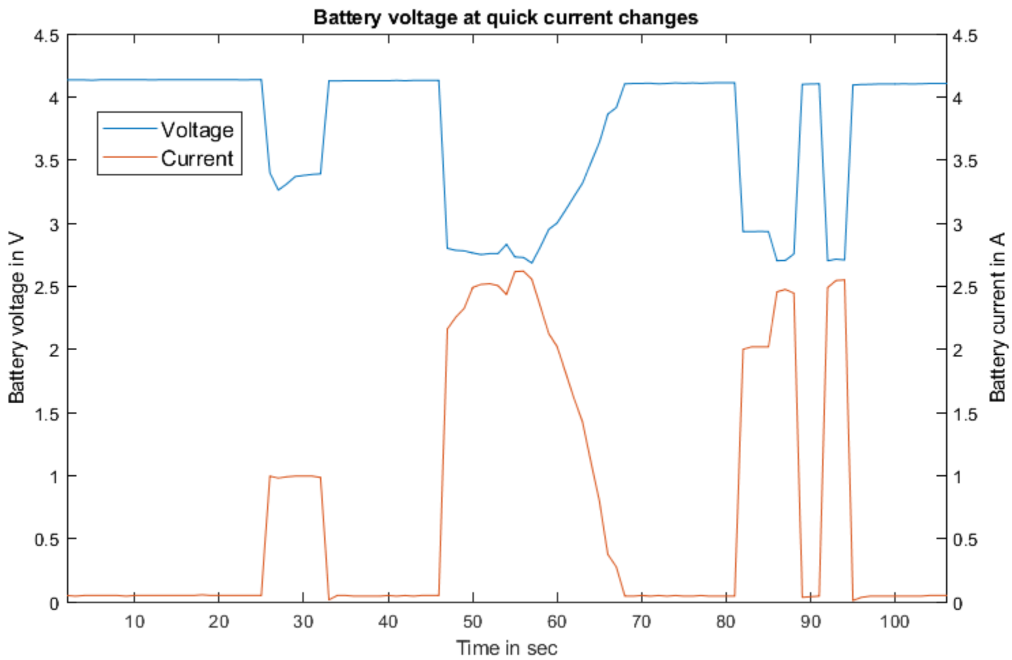

Figure 2.2: Battery voltage with rapid current fluctuations

Compared to other commonly used rechargeable battery types, Li-Ion batteries have a very high energy density. Average output voltage and current are both high while the low self-discharge and lack of memory effect, which is when batteries permanently lose capacity if recharged when not fully discharged, makes them useful in a wide range of applications [7]. The main disadvantage of Li-Ion batteries is that they are very sensitive to mistreatment and can catch fire or explode if they are overcharged, overheated or physically damaged. If overdischarged or used in a too cold environment, the lifetime may be permanently shortened. The general temperature range for use is between -25 to 45 °C for discharging, and 0 to 45 °C for charging [7].

2.1.1 Multiple batteries

Li-Ion batteries are manufactured in single cells with nominal voltage of 3.6-3.7 V. These cells are then often configured in different ways to either increase voltage, capacity or both. For additional capacity, cells are connected in parallel into what is called a block. Combining either cells or blocks in series provides increased voltage in steps of the nominal cell voltage. It is this configuration that is then called a battery. Multiple batteries in parallel and/or series are then called a battery pack [1].

2.1.2 Discharge rating - "C-rating"

One important battery property is the discharge rating. It specifies how fast a fully charged battery can discharge its entire capacity. The baseline is defined as one hour, meaning that a battery with a discharge rating of 1 C will be fully discharged in one hour. Following the same principle, a battery with a discharge rating of 2 C will therefore be empty in 30 minutes and so on. The discharge rating is also useful when determining the maximum flow of current through the battery. The maximum current is given by multiplying the battery's capacity by the battery's C-rating.

2.2 Battery management systems

While all BMS share the same goal of monitoring the batteries, there are several different BMS topologies available, with different benefits and drawbacks. In this section, the most common BMS topologies are presented, as well as the relevant available sensor options for measuring voltage, current and temperature.

2.2.1 BMS topologies

In a centralized BMS, all of the sensors within the battery pack are connected to one single central unit. This simple setup is compact, easy to repair and is generally the cheapest alternative. When the number of battery cells or the distance between cells increases, the length and number of the wires used to connect the sensors to the central unit can become an issue with regards to cost, weight and reliability [1].

A modular BMS utilizes several central units instead of only having one. This allows the central units to be located closer to the batteries they monitor, reducing the necessary wire length. It also allows for a more flexible BMS, where more modules and battery cells can be added later on. The cost and complexity is increased, as there now must be some redundant hardware and communication between the modules [1].

When using a distributed battery system, the electronics for monitoring a cell is placed directly on that individual cell. The system can be configured either so that all of the measuring units send their data to a central unit for further processing, or that they act independently. A setup like this minimizes sensor wire length, while also allowing for maximum modularity. It does however further increase system cost and complexity, as a lot of additional hardware and communication is now needed [1].

2.2.2 A standard BMS setup

A standard off-the-shelf BMS is conceptually simple, with limited functionality. It is based around the centralized topology, meaning that it only has one central unit responsible for collecting all the measurements from the sensors. Instead of measuring on every individual cell, one set of sensors monitor a pack of cells together. The sensors are connected to the central unit through a series of wires. The price of such a system varies greatly depending of specific application, but is in the range of 50-150 Swedish crowns per cell within the system [1].

2.2.3 Voltage measuring

Since Li-Ion batteries have a limited voltage range in which they operate, voltage measurements are important to keep the voltage within this range at all times. There is only one commonly used method for this measurement, but it can be applied in different ways. The most relevant of these different applications are explained here.

A conventional digital voltmeter, such as the one found in most commercial multimeters, interprets the voltage as an analog signal. This signal is then converted to a digital signal using an Analog to Digital Converter(ADC), where the resulting numeric number represents the voltage. To minimize impact on the circuit, voltmeters have a very large input resistance, usually 10 MΩ or more, limiting the current flowing through the sensor.

In many cases, microcontrollers come with an ADC as standard. Instead of having a dedicated voltage sensor on the Printed Circuit Board(PCB), this microcontroller ADC can be used to measure voltage directly. Depending on the application and the voltage range that is to be measured, extra components may need to be added depending on application.

2.2.4 Current measuring

Measurements of the current flowing through the battery are necessary to determine the battery's state of charge as well as detecting possible problems, such as short circuits. Two of the most common ways of measuring current are Hall sensors and shunt sensors, each with benefits and drawbacks.

The most common way of measuring current is by using a shunt resistor. A low resistance resistor, usually only a few milliohms, is placed in parallel with the sensor. This creates a small but measurable voltage drop over the shunt resistor, which can be amplified for easier measuring. Since both the voltage and resistance are now known, Ohm's law can be used to calculate the current flowing. This gives a simple and reliable way to measure current using few components. Drawbacks include limited current capacity as well as an unavoidable power loss from the shunt resistor [8].

To measure very large currents, a Hall sensor can instead be used. When current is flowing through a conductor, it produces a magnetic field perpendicular to the current's direction. If another conductor is placed nearby, a voltage difference is produced in it by the magnetic field, which is called the Hall effect. This voltage can be measured and used to determine the current flowing in the other conductor. This allows for measuring currents in a conductor without any of the measuring equipment being galvanically connected to the conductor, protecting it from high currents and voltage transients. It also allows for reliable measuring when the temperature changes. The main drawback of Hall sensors is limited accuracy and risk for interference. The sensor must also be calibrated frequently [9].

2.2.5 Temperature measuring

Li-Ion batteries are sensitive to temperature, with a safe operating range for discharge around -25 °C to 45 °C [10]. If operated outside this range, the lifetime and capacity of the battery could be significantly reduced. In some cases, too high temperature can result in the battery catching fire or exploding. To prevent this from happening, it is important to know the temperature of the batteries at all time. The temperature can also indicate other problems, such as partly shorted circuits or cells.

Themost important factor when attempting to measure temperature accurately is the position of the sensor. For batteries, which often have a metal casing, the two usual options are either internal or external measurement. For internal measurement, the sensor is placed within the electrochemically active area in the cell, while external measurement instead places the sensor on to or in close proximity to the cell casing.

While internal measuring is always more accurate, it is also more complex and expensive to manufacture, since it goes beyond of the common battery standards that already exist. The difference in precision between internal and external measuring increases as rate of charge or discharge increases. At a low discharge rating, there is almost no difference between the two options [11].

2.3 Communication

The communication between the battery sensors and the processing unit is a central part of every BMS. The choice of technology and protocol affects many of the crucial system properties, such as range, power consumption and the maximum number of measuring units in a system. Only wireless technologies are presented, as this project does not consider other options.

2.3.1 Wireless communication standards

Several wireless communication standards are available for the project, they are however not equal. Range, power consumption, performance, reliability and simplicity are researched for the chosen standards. The researched protocols are Bluetooth Low-Energy (BLE), Near Fields Communication (NFC), ZigBee and Wi-Fi. The possibility to use a self designed non-standardized protocol is also researched.

The Bluetooth Low-Energy technology is based on the regular Bluetooth standard, but with significantly reduced power consumption. Like the regular Bluetooth, it operates on the commonly used 2.4 GHz band together with other standards such as Wi-Fi. While regular Bluetooth maintains fixed connections between units, BLE only makes a connection when necessary [12]. The range is similar to regular Bluetooth, usually at least 10 m. The data rate is low compared to standard Bluetooth, since the technology is designed to fit devices that send data a few times a second, or less [13]. Since Bluetooth is widespread and commonly used technology, the unit price for chips is relatively low.

NFC is a set of communication protocols designed to function at very short range, usually less than 10 cm. It uses the magnetic field rather than the accompanying electrical field, since the electrical field is less dominant in this short range. The short range allows one of the two parts to be completely passive, where power is induced into the passive part from the active part when necessary. It has a low power consumption and adequate performance [13].

ZigBee is a technology that in many ways is similar to the Bluetooth Low Energy. It is designed to have low power consumption, with limited data rates as a result of that. Range is at least 10 m, but it can be extended if the environment allows it. One of the main features with ZigBee is that it utilizes mesh networking, in which the data travels through the different nodes within the network to reach the far away nodes better. A mesh setup therefore avoids important hub nodes and will still function if some node in the network fails. It can be operated either on 868 MHz, 900 MHz or 2.4 GHz [14].

The Wi-Fi technology is based around the IEEE 802.11 standards and is the most common technology for distributing wireless internet to devices such as personal computers, phones and tablets. It is most commonly used on the 2.4 GHz band but can also be used on the higher 5 GHz band. The connection range varies based on the access point and the environment, but is generally at least 20 m [15]. Wi-Fi is optimized towards large data transfers and therefore has a relatively high power consumption [13]. It is also relatively difficult to implement, particularly the hardware requires tight tolerances to ensure that the specification for radio performance is followed [16].

Instead of using any of the standard RF protocols, a self-designed protocol could be used. The main benefit of this would be that the protocol could be tailored specifically for the application, both in terms of performance, frequency and packet setup. Drawbacks include that there exist no pre-made hardware or software solutions. The most common frequencies for a self-designed protocol are 434 MHz, 868 MHz or 2.4 GHz as these are unlicensed bands, open for any use.

The 2.4 GHz band shares the same frequency as Bluetooth and Wi-Fi and is therefore prone to interference. It is also intended for high data transfer rates, with a matching power consumption. The unlicensed 868 MHz band offers a simple way of transferring data. Without set protocols, simply sending raw data to any receiver tuned to the same frequency is possible. Range is high with above 200 m even at low power input while the data rate usually is below 500 kbps [17]. High data rate applications are therefore not suitable for the 868 MHz band [18] [19]. These properties are similar for the 434 MHz band, but the lower frequency allows for an even longer transmit range, but also reduced potential data rate.

2.3.2 Antennas

For small wireless applications designed for broadcasting, two types of antennas are common; the monopole and dipole antenna. A dipole antenna consists of two wires with a length of $\lambda/4$ each, for a total antenna length of $\lambda/2$. The signal generator is then placed on the midpoint of the wire, as seen in figure 2.3.

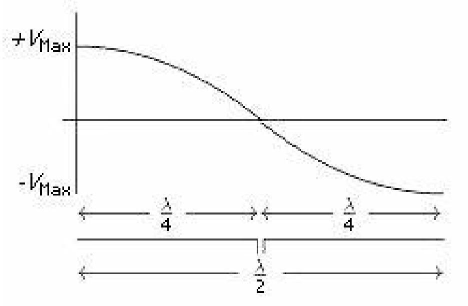

Figure 2.3: A dipole antenna a half of a wavelength [20]

A monopole antenna is basically a dipole antenna with the ground plane acting as one of the dipole arms as seen in Figure 2.4. This reduces the quality of the transmitted signal, but also halves the necessary antenna length.

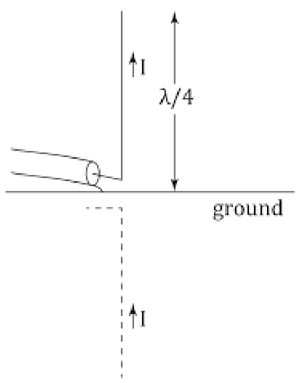

Figure 2.4: A monopole antenna a quarter of a wavelength [21]

For both types of antennas it is common to strive for a impedance match between antenna and filter. This is due to the fact that maximum amount of energy is transmitted when this criteria is fulfilled, if mismatched more energy will be lost to ground. To achieve this matching, additional passive components are connected between the filter and antenna. Adding length to the antenna is also a possible method of changing the impedance in order to impedance match the system [22].

2.3.3 Modulation

When transmitting data, it is common to have a carrier frequency much higher than what the intended data rate is. This allows the carrier frequency to be chosen for ideal range, penetration depth or licenses standard and to have a flexible data rate injected in the carrier frequency. When modulating this higher carrier frequency, numerous methods are available. They all stem from three main modulations; frequency, amplitude and phase. They are often referred to as frequency shift keying (FSK), amplitude shift keying (ASK) and phase shift keying (PSK) and can be seen in figure 2.5.

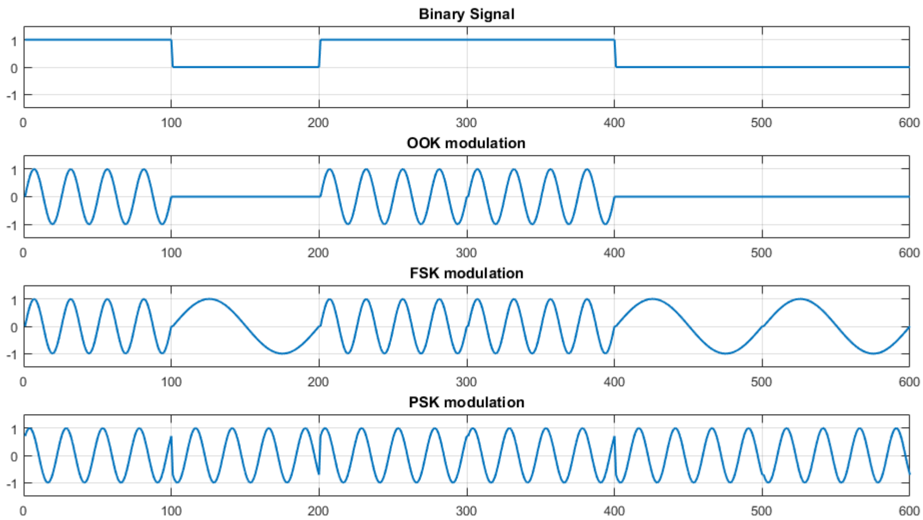

Figure 2.5: The three basic modulation types, where OOK is ASK with 0 amplitude at binary 0

FSK is a modulation where two frequencies make up the data, a logical 1 could be represented by f while a 0 could be represented as $f/3$. This means that amplitude changes do not change the data received. However, it does not have a good bandwidth compared to ASK or PSK. ASK, or on-off keying (OOK) as it is sometimes referred to as, is the simplest modulation. The carrier frequencies amplitude is changed between two values, where one value is zero. This modulation is most susceptible to interference from other sources while a clear advantage is that transmission time is reduced. Finally, PSK is the modulation of signal phase. In its simplest form, a binary 0 could be $0°$ phase while a 1 then would be $180°$ phase. This offers the same data rate as ASK while being less susceptible to errors due to interference [22].

3
Method

This chapter describes the general process followed when developing the complete system. First the design considerations and priorities for the hardware system are discussed. A short description of the manufacturing process is also included. Under the software section, general stepping stones of the code evolution are described, including the implementation on manufactured hardware. Finally, the testing process and test setups are described in detail.

3.1 Hardware

The first step in the process was to decide what parameters should be measured and how to perform these measurements. Through literature studies, it was concluded that the only properties necessary to measure were voltage, current and temperature, as these are enough to determine the capacity and health of a battery. Another important aspect of the project was the wireless communication. The choice of technology and frequency for the wireless communication was essential to achieve desired functionality. When making this choice, focus was put on low power consumption, low risk of interference as well as at least medium range, while also being able to support a large number of units simultaneously.

Since there are several ways to measure the chosen properties, the next decision was on which sensors to use. The priorities for the design were a small PCB and low power consumption, so the decisions were made to match that. The specification required the design to endure large currents, reducing the number of viable measurement options.

With all of the components for the design selected, the schematic was made. Most of the selected components came with data sheets which had example circuits on how to use them. These example circuits were modified and adapted to fit together, while still maintaining the functionality of the individual components. Using the schematic, the PCB layout was then created. The components were placed in a way that minimizes PCB trace distances while also minimizing the amount of traces with a possibility for high current for fault protection.

The circuit boards were constructed by hand. Components were soldered using a solder paste dispenser and a reflow oven. Due to the small size of the PCB and the components, not every constructed circuit board became fully functional. To compensate, a total of 10 PCBs were constructed, where 5 of them ended up being fully functional.

3.2 Software

To develop and test the software, several Nucleo L073RZ development boards[23] combined with X-Nucleo-IDS01A4 868 MHz radio shields were acquired. The cards came with example code that demonstrated the radio capabilities, which became the base for the code. The code was modified so it could send outputs to a terminal on the host PC, which made bug fixing and general development easier. In the example code, the ADC is not utilized. Since the ADC was necessary for the measurements, code that utilizes it was produced. It was also based on an example provided by the manufacturers, but was modified extensively. The protocol used for the communication was also modified and made more extensive to include all the necessary information that would be transmitted. Finally, some modifications to the pin setup was made. Since the development boards have a different microcontroller version compared to the circuit boards, the pinout had to be modified accordingly.

3.3 Test and Verification

In this section, the processes for testing all the system features are presented. It is divided into two parts, where the first one describes the sensor tests while the second one describes the communication testing procedure.

3.3.1 Sensors

When testing the voltage and current sensors, the goal was to simulate the circumstances of real use, while retaining the ability to control all parameters. To achieve this, the battery was simulated by a variable power supply unit while a variable artificial load was used instead of a real load. This enabled control over the current and voltage applied to the system, which were then measured by the system. Keysight U1272A multimeters were used as references to determine measuring errors. After an initial test, it was discovered that both the current and the voltage sensor had small error offsets. After these had been corrected within the software, the tests were run again with better results.

When testing the temperature sensor, the system was placed in various environments, where the temperature was measured. A Keysight U1272A multimeter connected to a temperature probe was used as reference. After initial testing, it was discovered that the system's internal heat resulted in a small temperature offset compared to the probe. After it was corrected, the tests were run again.

When the system was placed outside in the sun, it was discovered that the temperature probe reacted to the higher temperature faster, which created a need to test the sensor's reaction time. For this test, both the probe and the system were placed in close proximity to a power resistor, which then was connected to a power supply to generate a large current, which rapidly heats up the resistor and enables measuring of the system reaction time compared to the probes.

3.3.2 Communication

After first testing the system's communication properties, it was discovered that hardware problems severely limited the performance. To evaluate the technology concept, further communication tests were performed with Nucleo L073R8 development boards instead of actual systems. A total of four Nucleo L073R8 boards were used as transmitters, where each was simulating a total of 10 systems by rotating system addresses and sending 10 times more frequently, for a total of 40 simulated systems. A more powerful Nucleo F401RE[23] was used as the receiver

For the testing, each simulated system sent 100 packages, for a total of 4000 packages sent. When they all had been sent, the receiver displayed the total amount received from each simulated sender as well as the average number. The test was then repeated with other protocol configurations and through interference tests. Strong Bluetooth and Wi-Fi signals were introduced by the use of a laptop and cell phones communicating, while 868 MHz interference was produced by yet another Nucleo development board, broadcasting nonsense.

4
Implementation

In this chapter, all the systems different parts are explained. It is divided into five sections; Battery, Circuit Board, Sensors, Software and Wireless Communication. Any choices made for the design are presented and explained here. An overview of the system can be seen in figure 4.1.

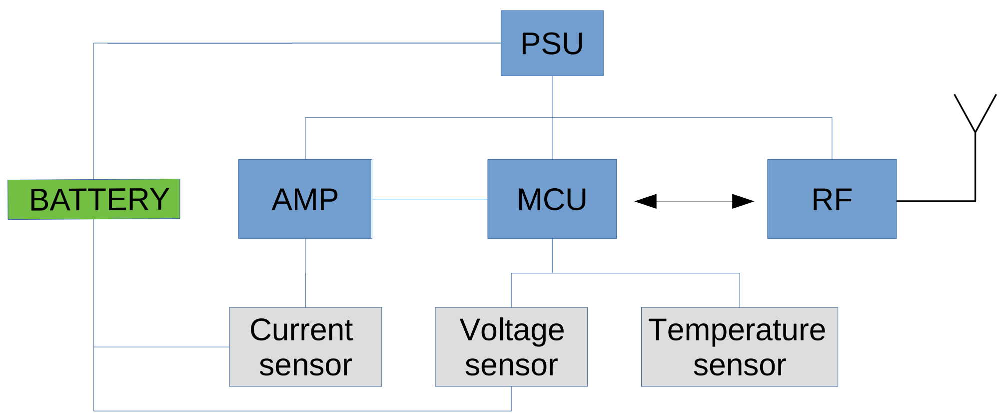

Figure 4.1: A system overview, ICs are shown as blue squares. Blue line represents a analog signal or power, black arrows shows digital data lines.

In the system, the Power Supply Unit (PSU) draws power from the battery and provides steady and regulated power to all other components. The amplifier (AMP) is used to amplify the tiny voltage drop over the shunt resistor used for current measuring. An ADC in the Micro Controller Unit (MCU) is connected to the battery through a voltage divider to give a voltage reading. The MCU itself also provides a temperature sensor. The received sensor data is then sent to the RF chip which in turn broadcasts this on the 868 MHz band.

4.1 Battery

There are batteries in almost every imaginable size and shape with vastly different capacities and applications. Since this project is a proof of concept and not a finalized product, a very common Li-Ion cell is used. The cell chosen as the standard is the Panasonic NCR18650B, shown in Figure 4.2. It follows the 18650 cell standard, which means that it shaped as a cylinder with a hard metal casing. It has a height of 65.0 mm and a diameter of 18.5 mm, with connectors on both sides of the cylinder.

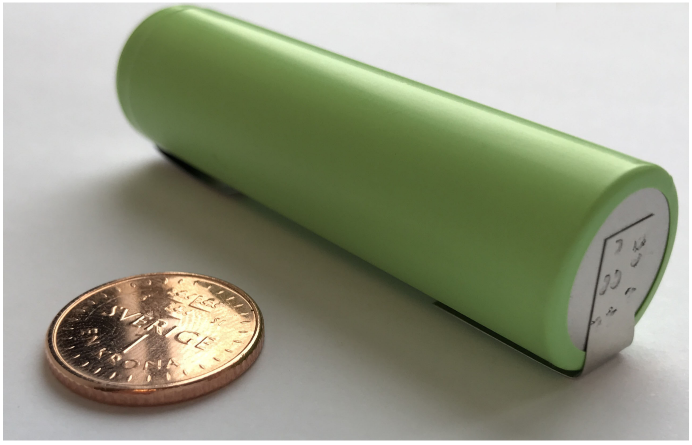

Figure 4.2: A Panasonic NCR18650B cell, with a coin next to it for size comparison.

When it comes to voltage, capacity and temperatures, the NCR18650B cell has the following properties [10]:

- **Rated Capacity -** 3200 mAh
- **Nominal voltage -** 3.6 V
- **Voltage range-** 2.5 - 4.2 V
- **Charge temperature -** 0 - 45 °C
- **Discharge temperature -** -20 - 45 °C
- **Storage temperature -** -20 - 45 °C
- **Discharge rating -** 2 C

The voltage provided by the battery changes with the remaining capacity. A fully charged healthy battery provides a voltage of 4.2 V, while a drained battery only produces 2.5 V. Since the battery lacks a protective circuit, it is possible to charge it beyond 4.2 V and discharge it below 2.5 V, but this has a high risk of permanent damage to the battery. This voltage range is therefore considered as a safety span, where the battery can be used safely.

A discharge rating of 2 C, as explained in section 2.1.2, means that the battery will drain its entire capacity in 30 minutes if operated at maximum current. It also means that the maximum current flowing through the battery is known to be 6.4 A, as calculated in Equation 4.1.

$$A_{MAX} = 2 \cdot C = 2 \cdot 3200\text{mA} = 6.4\text{A} \tag{4.1}$$

4.2 Circuit Board

The complete system is composed of a microcontroller unit (MCU), an RF communication chip with filter, impedance matching and antenna, sensors and a power supply. It is based on the Nucleo L073RZ development board design from STMicroelectronics, but with significant modifications to match the specifications of this project.

The PCB is manufactured in standard FR-4 laminate with a copper thickness of 70 μm. The board is dual layered and the entire design fits on a 65 by 18 mm area, matching the battery footprint perfectly. The board is divided into two areas. The larger area is where the components are placed and it has ground planes on both sides to increase operational reliability and reduce interference from RF. The smaller area of the card is designated for the antenna and no ground planes are present to ensure low signal induction back into the system. The layout with the two areas is shown in Figure 4.3.

The entire system is composed of Surface-Mounted Devices (SMD) where all basic passive components follows the 0603 area standard which in metric units is 1.6 mm x 0.8 mm. While smaller passives are commonly used and could give beneficial performance in the RF circuit, smaller footprint would greatly increase the accuracy needed when hand placing components. The possibility to manually modify or re-solder components after initial manufacturing is also deemed necessary, which is why this larger standard is chosen. All Internal Circuits (ICs) have 100 nF decoupling capacitors placed as close as possible at all power pins.

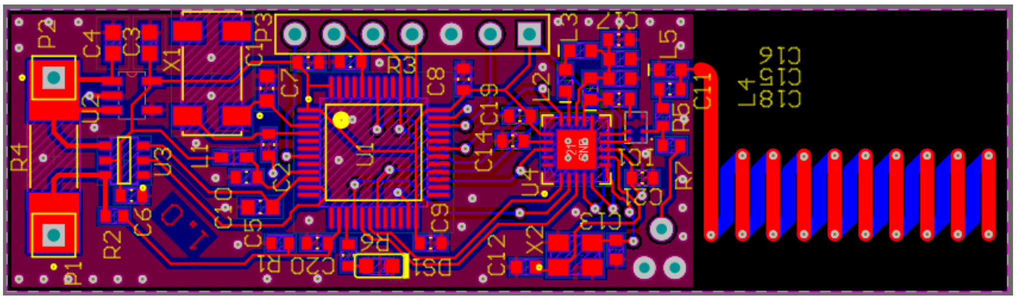

Figure 4.3: PCB layout for manufacturing, red and blue represents copper on top and bottom layer respectively. Slightly transparent colors shows it is a ground plane while clear colors is for signal traces. The black area is bare laminate.

4.2.1 Microcontroller

This design is based upon the STM32L053C8T6TR[24], which is an ARM MCU, part of STMicroelectronics ultra-low-power series. It contains several ADC inputs, SPI and an internal temperature sensor, all necessary for this project. Running at 32 MHz, 8 kB RAM and with 64 kB programmable memory, this MCU has more than enough performance to run the communication and manage the sensors. The MCU was chosen due to the facts that it is one of the cheapest L0 ARM MCUs, there exist development boards with a very similar MCU and that given the designs need it fits the bill. The schematic design is based on the provided datasheet [24].

To flash the MCU with new code a pin header is placed on the card as seen in figure 4.3 and in schematic form in A.1. To this header the following pins are connected:

- **VDD -** Allows for an external power source enabling both MCUs to be supplied by 3.3 V necessary for communication.
- **TMS -** Data communication.
- **GND -** Shared ground.
- **TCK -** Clock signal.
- **SWO -** Optional clock signal.
- **BOOT0 -** Controls the boot loader, by pull-down resistor default is set to system memory.
- **NRST -** Resets the MCU when grounded.

4.2.2 Power supply

While it is possible to supply power to the components directly from the battery, its varying voltage makes implementations complicated, especially to have a reliable reference voltage and to ensure a safe working condition for all components. With an operational battery voltage potentially as low as 2.5 V [10] and components with lowest operation voltage of 2 V, a Low-Dropout Regulator (LDO) with as low voltage drop as possible is preferred. Texas Instruments TPS78223DDCT is used since its low voltage drop of 130 mV while providing 150 mA, low loss of 500 nA and relatively low cost makes it ideal in this application [25]. Two other beneficial abilities of this component are that it needs no load to produce a constant voltage and can withstand the reverse current occurring when the device is powered from a separate card during MCU programming. It is configured to connect all powered components with 2.3 V for the entire operational voltage range of the battery, with a safety margin of potential operational voltage up to 5.5 V. It is routed in accordance with its example schematic provided by Texas Instruments, which can be seen in schematic A.3.

4.2.3 Wireless Communication

Wireless communication is handled by a SPIRIT1 IC by STMicroelectronics. This is a low data rate low power transceiver with a data rate up to 500 kbps. The SPIRIT1 is sent data over SPI from the MCU, which is then processed and sent to the antenna. It supports multiple settings regarding modulation and encryption. Clock signal is provided by an external 50 MHz crystal and is setup according to data sheets by STMicroelectronics [26] [27]. Solder pads for a balun BALF-SPI-01D3, used to balance incoming unbalanced signals, are placed in close proximity to the chip. Since the decision was made for the system only to send data, the balun is not necessary and is therefore unused[27].

4.2.4 Antenna

There are several kinds of possible antenna solutions but with range being of less importance than size and cost a quarterwave monopole PCB antenna is chosen. Since the PCB antenna only consists of copper traces and a few passive SMD components the cost in mass manufacturing is almost negligible. To reduce time to production a helical PCB antenna based on a design published by Texas Instruments is used [28]. This is the most efficient PCB antenna design with a power efficiency of 66% given the size constraints, with only 20x18 mm of usable area left [29]. It is composed of 18 6x1 mm PCB traces connected with vias to form a continuous coil antenna as seen in figure 4.4. Total length is 127.5 mm where a quarter wave length of 868 MHz is 87.5mm, this difference is due to the impedance match with the rest of the circuit composed of a 12 nH inductor (L5) and a 1 pF capacitor (C11) as seen in figure 4.4 and schematic A.2. For increased reliability, a through hole solder pad is placed by the transmission line for the possibility of using a wire antenna. This antenna, lacking the impedance matching should be 87.5 mm. Choosing which antenna to use is done by placing a 0 ohm resistor at either R5 or R7.

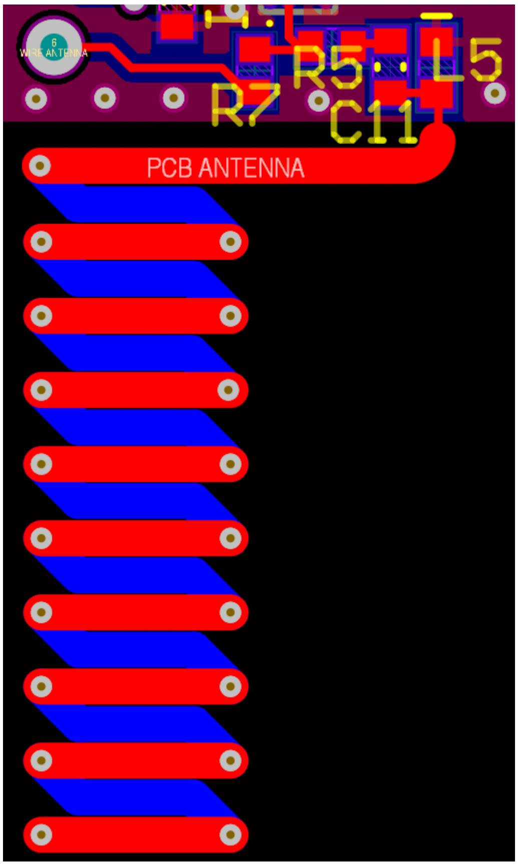

Figure 4.4: Helical PCB antenna for 868 MHz, red traces represents copper on the top layer while blue represents copper on the bottom layer

4.3 Sensors

Using the right sensors is a crucial part for the project. When choosing a sensor, there is usually a trade-off between accuracy, size, power consumption and cost, in this project, small physical size and low power consumption. The sensors are chosen to be able to handle the different properties of the Panasonic NCR18650B cell, with regards to its maximum current, voltage range and temperature ranges.

4.3.1 Voltage

Voltage measurements are done using the MCUs internal ADC, which provides 12-bit resolution. With the MCUs analog reference voltage being 2.3 V, the ADC can not be directly connected to the battery without exceeding the maximum allowed voltage. Instead, a voltage divider is used. Two equal 49.9 kΩ resistors ensure safe working conditions for the ADC. The first resistor is placed very close to the power line to reduce the risk of short circuiting potential high currents. The values of the resistors are chosen as they are the highest tolerated input impedance of the ADC while still maintaining proper function. The voltage divider does however cause a constant current drain of up to 37 μA.

Parallel to the ADC input and ground a 10 nF capacitor is placed to filter out voltage swings and give a more stable reading. In this setup, the total unadjusted error is typically 2 LSB [24], which translates into a 1.1 mV error. The cost and increased size of a system with a separate ADC makes using the internal ADC a good choice. An external ADC could result in more accurate readings, but is not necessary for this application. The voltage divider caused a small constant offset in measurements, which is corrected by adding a +11 mV offset within the system software.

4.3.2 Current

For current measurement, a 0.001 Ω shunt resistor is inserted into the load line, causing a very small voltage drop. Kelvin connection is used to ensure measurements are solely of the resistors voltage drop [30]. This voltage difference is then amplified using a Silicon Labs TS1101-200EG6 bi-directional current-sense amplifier. The amplified signal is converted to a digital readable number by the ADC within the microcontroller. The amplifier has another digital output connected to the MCU which represents the direction of the current measured.

Since the load line runs on the PCB it needs to withstand potential high currents. Calculations for the tracing of the load line are done using Saturn PCB design. A temperature rise of 20 °C is a commonly acceptable limit [31]. The PCB traces are kept the same width as the shunt resistor and as short as possible. With these restrictions, a copper thickness of 70 μm is needed for the potential maximum current of 6.4 A drawn from the battery. When soldering these components a layer of solder is formed on the copper traces, which further increases the conductivity. The calculations are shown in appendix A.5 and A.6.

The shunt resistor is chosen for current measurement since it is a reliable and accurate solution. While it does generate an unavoidable power loss over the resistor, the very small size of the resistor makes it acceptable. As seen in equation 4.4, the power loss during maximum load is 43 mW, which is well below 1% of the total power drawn from the battery. Since the shunt resistor is the only component in the design that consumes more power as the battery current increases, this indicates that the system never will use more than 1% of the total battery power.

$$P_{loss} = I_{max}^2 \cdot R_{shunt} \tag{4.2}$$
$$P_{loss} = 6.4^2\text{A} \cdot 0.001\Omega = 41\text{mW}$$
$$P_{cell} = V_{nominal} \cdot I_{max} \tag{4.3}$$
$$P_{cell} = 3.6\text{V} \cdot 6.4A = 23.04\text{W}$$
$$\frac{P_{loss}}{P_{cell}} = 0.18\% \tag{4.4}$$

While being an accurate solution for current measuring in general, measuring very small currents with this setup is problematic. Both the amplifier and the ADC provide some error to the end result, which must be considered. The biggest factor is the ADC, which has a maximum offset error of 2.5 Least Significant Bits (LSBs). At high voltages this error becomes negligible, but will have a more significant impact when measuring no or very low current. The amplifier has an error of 0.6%. The offset error results in a maximum error of 6.285 mA, as shown in equation 4.8.

12 bit ADC (a total of 4096 bits) that measures 0-2V

$$\frac{2}{4096} = 0.49\text{mV}/\text{LSB} \tag{4.5}$$
$$Error_{max} = 0.49\text{mV} \cdot 2.5 = 1.47\text{mV} \tag{4.6}$$

Amplifier conversion rate: 200mV / 1A

$$iError_{max} = \frac{1.47}{200} \cdot 1A = 6.25mA \tag{4.7}$$

Finally, the 0.6% error from the amplifier is added

$$6.25mA \cdot 1.006 = 6.285mA \tag{4.8}$$

When operating the battery at low currents, this error would be a significant part of the result, which would cause severe measurement errors. However, this is not a problem in this application, since the current measurements main purpose is for capacity estimations. When operating at such low currents, the voltage level is still a reliable capacity indicator. When the current increases to a point where the voltage no longer can be used, this error is then negligible, resulting in full coverage of capacity measuring. A small constant voltage offset on the ADC, which shifts the field of measurement to 0.1 - 2.1 V would also solve the problem, but would require additional components and draw additional power, which is deemed unnecessary. The shunt resistor creates a small linear error which is corrected within the system software by multiplying all measurements by 0.97.

4.3.3 Temperature

The ADC contains an internal temperature sensor. This sensor comes pre-calibrated from factory and has an accuracy of ± 1 °C [24]. The limited accuracy of the sensor, combined with the fact that the sensor does not measure the battery directly, results in low accuracy readings. While not optimal, the temperature measurement is done mainly to keep the cells within their temperature operating range. Due to the severe consequences of Li-Ion batteries overheating, battery manufactures use large safety margins when specifying operating temperature ranges, making very accurate temperature measurements unnecessary. To compensate for the small amount of heat generated within the MCU itself, an offset of -2 °C is added within the system software.

4.4 Wireless Communication

For this project, low power consumption, at least medium range and need to communicate with many units are the main priorities when it comes to wireless communication, while high performance is not necessary. Based on this, a self-designed protocol broadcasted on a relatively low frequency is considered the best option. In this section, the frequency, radio space regulations, the protocol and communication strategy are presented.

4.4.1 Frequency

Since the radio space is limited, many of the available radio bands are restricted for specific applications, such as governmental, military or others. Many other bands are commercially available, but requires a license and are usually already crowded. This leaves a few frequency bands with low or no restrictions for everything else. These are commonly the 433 MHz, 868 MHz and 2.4 GHz bands. This system runs on the 868 MHz radio band. The system range and penetration power largely depends on the frequency used, where lower frequency allows for longer range and more penetration at the same transmit power. However, since the range requirement is only 5 m with limited need for penetration, either frequency would provide sufficient range and penetration. Maximum performance is also dependent on frequency, but in this application either frequency is able to handle the small amount of transmitted data.

The 2.4 GHz band is already very crowded and therefore prone to interference, since the commonly used Bluetooth and Wi-Fi protocols both utilize it. While otherwise having good properties, the risk of interference with Wi-Fi networks or cellphone Bluetooth connections disqualifies it from this system. The 868 MHz and the 433 MHz bands demonstrates similar properties in bands that are open to use, but less crowded than the 2.4

GHz band. Lower frequency signals require a longer antenna to pick up, so the 868 MHz system is chosen to minimize the antenna length and therefore the PCB size.

4.4.2 Regulations

As previously mentioned, there are many regulations and restrictions regarding which frequencies can be used and also how they should be used. Since these regulations vary depending on the country, the system is designed for the Swedish regulations.

The regulations, issued by Post och Telestyrelesen, specifies that for the 868 MHz band, a transmitter is only allowed to transmit at a power of 25 mW. They also state a maximum duty cycle of 1%, which translates to 36 seconds of transmission every hour [19]. This regulation is valid for every individual transmitter and not for the system as a whole, so as long as no individual measuring unit breaks the 1% limit, the system follows the regulations completely.

4.4.3 Communication strategy

When dealing with multiple devices communicating via radio in close proximity, problems with lost packages and interference may start to appear. If two or more measuring units transmit simultaneously, packages may get lost. To minimize this interference, a communication strategy is implemented which dictates when and how data is sent. It is very important to minimize the amount of lost packages, since the information within the packages may be crucial for the system to properly manage the batteries.

To avoid complicated and fragile synchronization systems for transfers, the senders instead send their packages at random times. While not guaranteeing free passage for packets, the risk of another sender transmitting a package at exactly the same time is low. To further reduce this risk, each sender transmits the same packet twice, both times at a random point in time. Since the battery values are to be measured at least every second, the sender sends two packages every second with the same information as shown in Figure 4.5. If one gets lost, the other one is still likely to make it, which results in no lost data.

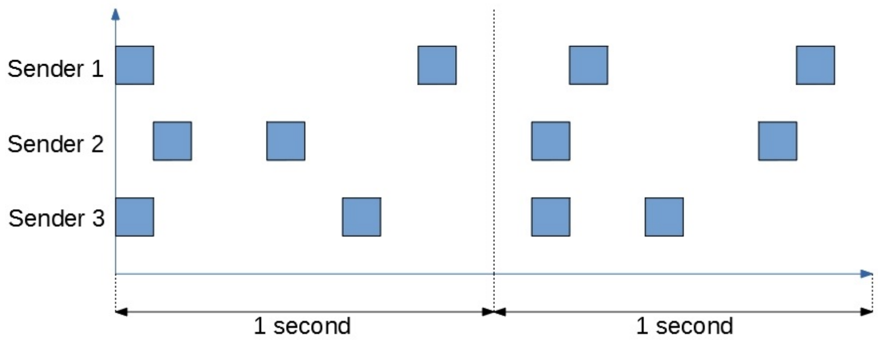

Figure 4.5: Communication strategy concept. Even if two packages are sent at the same time in one instance, it likely will not happen twice.

This strategy is chosen because in applications with a relatively low amount of transmitters, it performs better than the simpler strategy where each package is only sent once. This can be determined by calculating the theoretical probability of package collisions depending on the number of transmitters for both cases, as shown in Equation 4.9 and Figure 4.6. This assumes a packet length of 5 ms and a transmission period of 1000 ms.

$$P_{single} = \frac{5 \cdot n}{1000} \qquad (4.9)$$

$$P_{double} = \left(\frac{5 \cdot n}{500}\right)^2$$

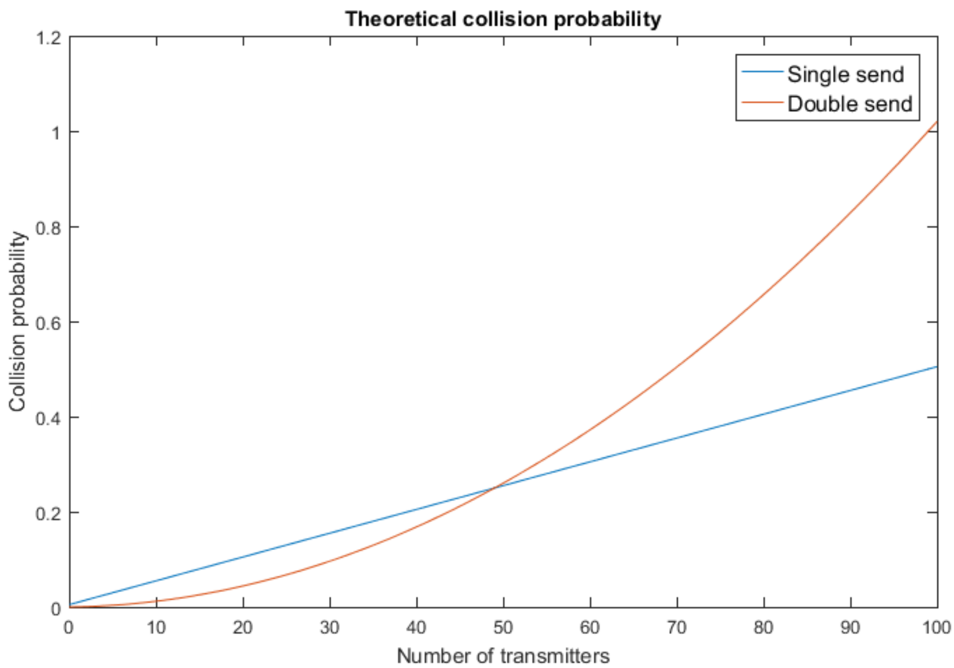

Figure 4.6: Theoretical probability of collision for both single and double send strategies as the number of transmitters increases

When communicating with 40 units, as was the minimum number within the project goals, the double send protocol is preferable since it reduces the package collision risk compared to the single send strategy. When 40 is entered as the number of units in Equation 4.9, the collision rate is 16% for the double send strategy and 20% for the single send strategy.

To minimize the number of transmissions, the system is configured so the measuring units only send data and the central unit only receives data. This means that no confirmation that a package has been delivered is sent back to the sender. This is not a problem since each package is sent twice, so the risk of losing data is already low. Additionally, a lost data packet, while not desirable, would not endanger the system if it does not happen regularly.

4.4.4 Protocol

For the transmission of data, a protocol is used. It is based on the Spirit1 BASIC standard[**?**] protocol, but with modifications to mainly the payload part to fit this project. The main goal of the protocol is to minimize data packet size, since this shortens transmission times and reduces power consumption. The protocol setup is shown in Figure 4.7.

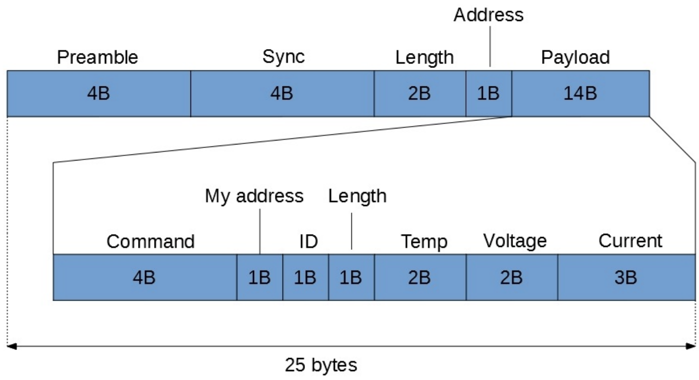

Figure 4.7: The communication protocol used data transmissions.

The preamble, sync and length fields of the protocol are predefined when following the BASIC protocol template and are necessary to be able to send packages. They are used as specified within the SPIRIT1 data sheet [26]. The address field should contain the given address of the receiver unit. The payload contains all of the actual information that is transmitted. The command data is again part of the BASIC protocol template and is left unchanged. The other fields in the payload are explained in the list below. A data packet has a size of 26 bytes, where 14 of these bytes are the payload.

- **My address -** The address of the sender, so that the receiver knows which sender unit that made the transmission.
- **ID -** Package ID that is randomly selected for each package. It is used for the receiver to determine if it has already received the package or not.
- **Length -** Length of the total data buffer, so that the receiver knows when to stop reading.
- **Temp -** Measured temperature. While one byte of data is sufficient to transmit the desired temperature range, it is not enough to also keep track of whether the temperature is positive or negative. An extra byte is therefore used as a sign.
- **Voltage -** Measured voltage. It is transmitted in millivolts, so two bytes of data is necessary.
- **Current -** Similar to the voltage, where two bytes are used for the actual value. Since the current can go in both directions, a third byte keeps track of the direction. Even though it could fit into two bytes, the third is added as a safety buffer, if the information sent would be altered later on.

4.4.5 Transmitter software

The duty of each unit is to collect data from all of the sensors and send it to the receiver with the right format and at the right time. To avoid aliasing in the input signal, the ADC samples each channel four times per second and uses the average from the four samples for the data that is actually sent. This filters out sudden unrealistic spikes that for example can occur when the load changes. Since the intended applications will not change load more than once every second, it also fulfills the Nyquist criteria and therefore avoids aliasing. This procedure is the same for all three things measured, since they all go through the ADC.

The ADC is set up in Multi Channel Single Conversion mode, which allows it to measure on multiple channels with a single sweep. The code is based on an example provided by the manufacturer, which is modified to match the necessary number of channels. To maximize accuracy, the ADCs internal VREF is measured and used for the other measurements, so the potential voltage error from the external power supply can be discarded as a factor in the measurements.

For the communication, the data is packaged according to the protocol. Over the course of a second, the same data packet is sent twice at semi random times. The first package is sent randomly within half a second. The sender then waits the remaining time until half a second has passed, before sending the packet again at a random time. This guarantees that no more than one packet is sent each half second, but two packets are always sent each second, while also keeping the times to send random. When the two packets have been sent, data is once again collected and the process is repeated. The address of the receiver is hard coded, so that no packages are sent to the wrong address.

Whitening or scrambling of data is used to help symbol tracking by reducing the amount of multiple 0s or 1s in a row. Whitening uses the XOR function on all payload data bits sent [26]. As for modulation, OOK is used since a logical 0 is represented by no transmission the overall system power consumption is reduced. The transmit power is set at 11.6 dBm or 14.45 mW, well below the maximum 14 dBm stated in the regulations. Baudrate is set at 38400 pbs.

4.4.6 Receiver software

The receiver collects the packages and checks the package ID. If the package received has already been received and thus only is a copy, the new package is discarded. If it is a new package, the data is retrieved and processed. In this project, it is only presented in a terminal window on the host PC for demonstration purposes. After each received package is handled, the receiver goes back and listens for more packages.

5
Results

In this chapter, the results from all tests performed on the system are presented. The test values have for most tests been summarized in graphs and figures for simplification, where all the exact measurements can be found within the appendix. For the sensor tests, additional graphs specifying the measurements errors are also presented. The basic test setups are also presented before each test result, with the entire testing process presented in Section 3.3.

5.1 Communication

When the communication capabilities of the systems were tested, some significant problems regarding both range and performance were detected. These problems were caused by the antenna, which is poorly impedance matched and is discussed furhter in Section 6.2.1. In order to test the protocol and technology concept as a whole, tests were also performed with Nucleo L073R8 development boards combined with 868 MHz RF shields. Since their radio technology is very similar to the developed systems, it is likely that a system with a fully functioning antenna would have very similar performance results as the development boards.

5.1.1 Scalability

A total of four Nucleos were used as senders, where each was simulating 10 sender units each for a total of 40 sender units. Each Nucleo sent 100 packages for eac simulated sender, for a total of 1000 packages sent. The test was repeated five times, with the average amount of received packages for each test presented in Table 5.1.

Table 5.1: Average amount of packets received for double send protocol

Test	1	2	3	4	5	Avg
Average	62	62	64	61	65	62.8

When using the double send protocol, which sends each package twice, an average package receiving rate of around 60% is achieved, which is significantly lower than the theoretical expectation of 84%, as calculated in Section 4.4.3. The simpler protocol concept of only sending each package once was also tested in the same way, with results shown in Table 5.2.

Table 5.2: Average amount of packets received for single send protocol

Test	1	2	3	4	5	Avg
Average	75	78	80	79	79	78.2

When the simpler protocol is used, the package receiving rate is increased to around 78%, which is close to the theoretical max of 80%, as calculated in Section 4.4.3. Additional tests where strong Bluetooth and Wi-Fi signals were sent in close proximity to the system were performed, but with no noticeable performance degradation. When other units using the same frequency as the system were introduced, a slight performance degradation was noticed.

This result indicates problems with the double send protocol, but also verifies that it is possible for 40 units to communicate. A package receiving rate of around 80%, while not optimal, is enough to get a good understanding of the battery status. Other forms of common RF communication, such as Bluetooth or Wi-Fi, could not affect the system performance, meaning that it is not susceptible to external interference from other common sources. The goal of having 40 units communicating without suffering from external interference can therefore be considered fulfilled.

5.1.2 Range and penetration

The range of the developed system is very limited. For good performance, the distance between sender and receiver can be no longer than 20 cm. If placed further away, a significant performance drop can be seen, with most of the packages being lost. The range is also dependent on the antenna angle. Certain angles provide better range, while some reduce the range to basically none. The signal can penetrate thinner objects at this range, but can not penetrate thicker objects, for example walls. This a noticeable problem when placing the circuit board parallel to a battery, as the metal casing absorbs all transmitted signals with no packages reaching the receiver.

When instead testing the range and penetration with a development board, the achieved range is well beyond what is deemed necessary, with no significant performance degradation even at distances over 15 m. Due to the relatively low frequency, the signal can penetrate most common objects. The signal was able to pass through multiple walls and other similar objects with no noticeable performance loss. It is therefore considered that the technology, with a proper antenna, has sufficient range and penetration power for the considered applications in this project.

5.1.3 Power consumption

Power consumption was measured using three systems. Measurements were carried out using a multimeter. Each test was run for two minutes, where the log function on the multimeter was used to determine the average consumption. The battery's nominal voltage of 3.6 V was used throughout the testing.

Two different power consumption tests were conducted. To determine hibernation consumption, a test with the transmission, sensors and ADC deactivated was carried out. To test full consumption, the second test was performed with the system running as it would in operation, with transmission, sensors and ADC sampling active.

Table 5.3: Power consumption, measured in mW

	Card 1 [mW]	**Card 2 [mW]**	**Card 3 [mW]**
No transmission or ADC	3.60	3.60	5.98
Transmission	19.8	19.30	23.76

Looking at the case of no transmission or ADC it is clear that the goal of 0.7 mW power consumption while idle is not achieved.

When the system is connected to a load, the additional power loss in the shunt resistor used for current measurements must be taken into account. With a variable load, EA-EL 9500-90 B two different scenarios were tested. First a low power test where the lowest possible battery voltage of 2.5 V and a current of just 0.5 A, resulting in 1.25 W power, was used. Secondly, a test at the highest possible power the load could produce, 4.2 V and 5 A resulting in 21 W. During these two test the power loss of the circuit board was measured using multimeters and the results can be seen in Table 5.4. From these numbers it is clear that with a total power consumption lower than 1.25 W the loss of the system could exceed the 1% limit stated in the goals.

Table 5.4: Total circuit board power consumption compared to the overall total power consumption

	Load Power [W]	**Card Power [mW]**	**Power of total [%]**
Card 1	1.25	11.7	0.93
Card 2	1.25	11.9	0.95
Card 3	1.25	12	0.96
Card 1	21	31.1	0.15
Card 2	21	30.9	0.15
Card 3	21	31.8	0.15

5.2 System sensors

In this section, results from the three different system sensors are presented. Each sensor measurement is compared to a reference measurement taken by a multimeter.

5.2.1 Voltage sensor

Measurements were carried out at 200 mV intervals starting at 2500 mV and ending at 4300 mV. Measurements were done using three systems, with no artificial load connected. Results are shown in Figure 5.1, where the exact measurements can be found in Appendix A.1 to A.3.

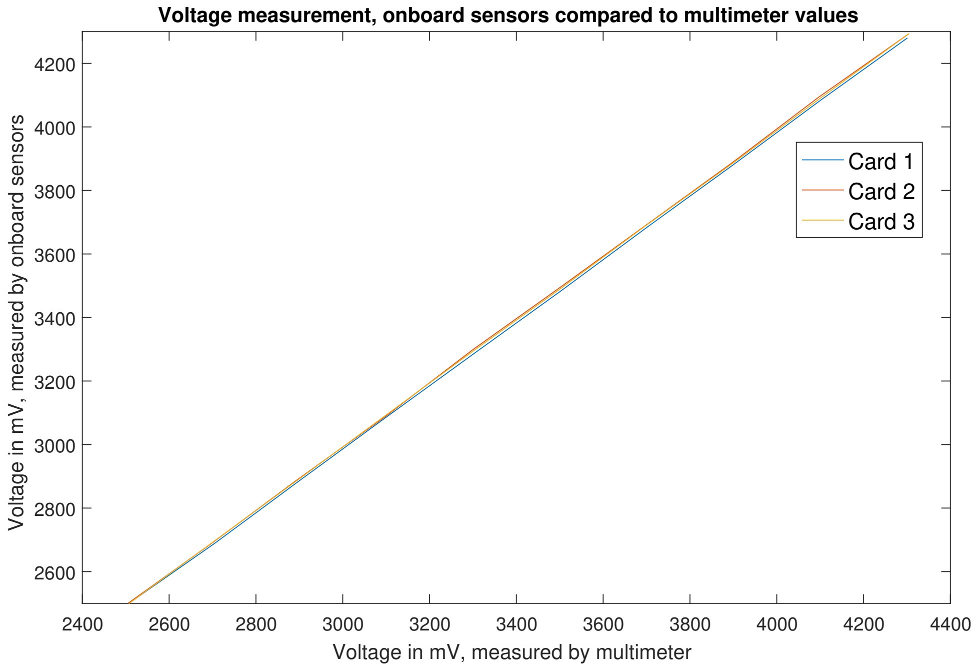

Figure 5.1: Voltage measurements performed with a multimeter compered to measurements done by onboard ADC

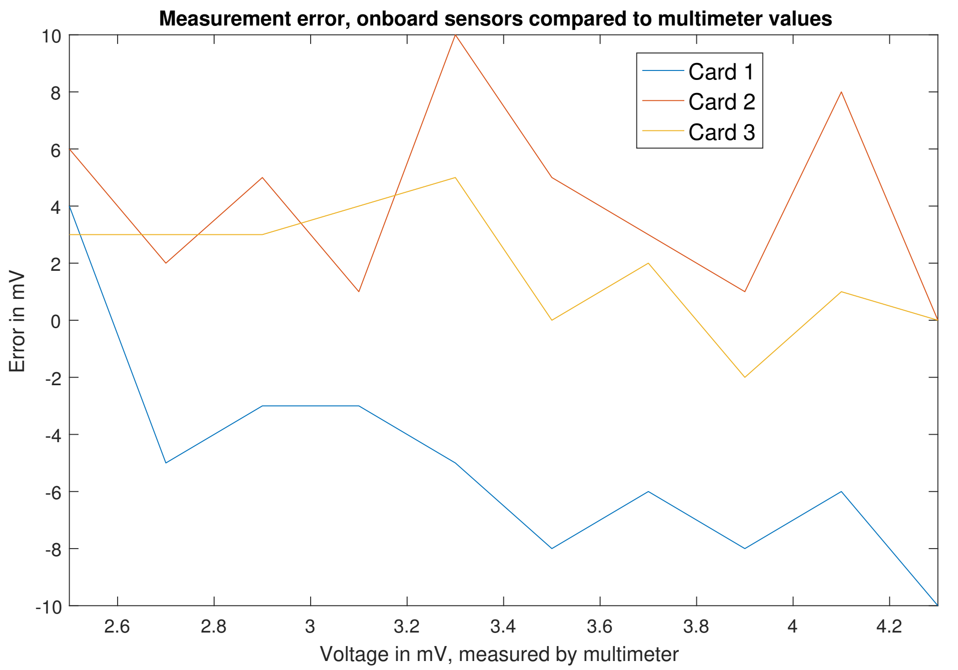

Figure 5.2: Measurement errors when comparing system sensors to multimeter values

Upon inspection of the measuring errors compared to the multimeter, shown in Figure 5.2, it becomes apparent that none of the systems had a voltage measurement error greater than

10 mV. The goal of 10 mV voltage measurement accuracy set in Section 1.4 is therefore considered fulfilled.

5.2.2 Current sensor

The current sensor was tested by connecting the system to a power supply and a variable load, EA-EL 9500-90 B. The load was then calibrated to generate specific currents through the system. These currents were then measured by both the system and a multimeter, with the results shown in Figure 5.3. The errors are displayed in Figure 5.4, measurements can be found in Table A.4 to A.6 in appendix.

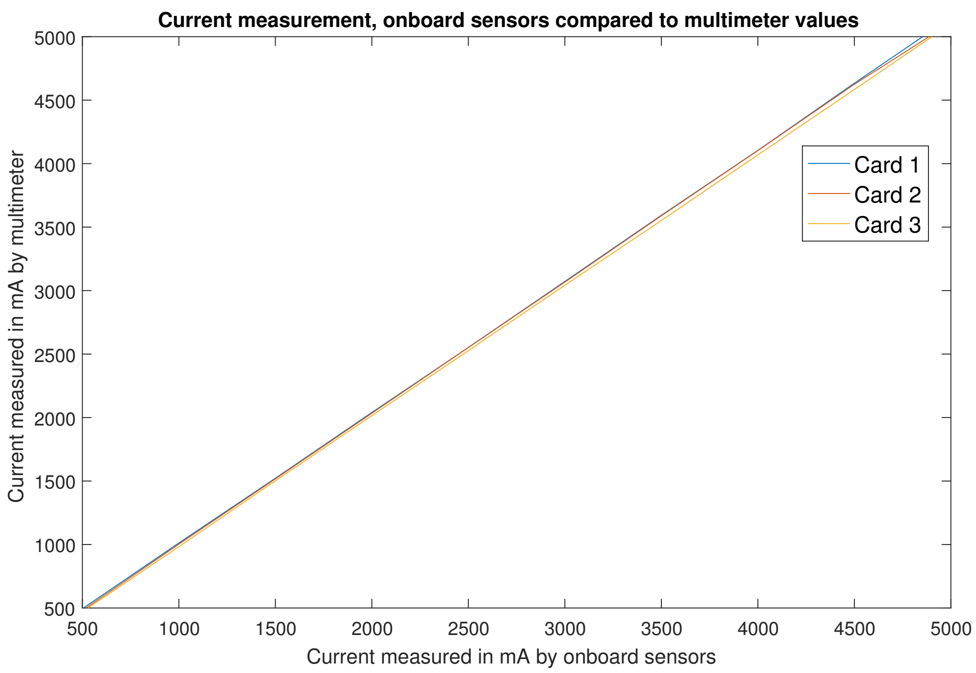

Figure 5.3: Current measurements performed with a multimeter compered to measurements done by onboard ADC

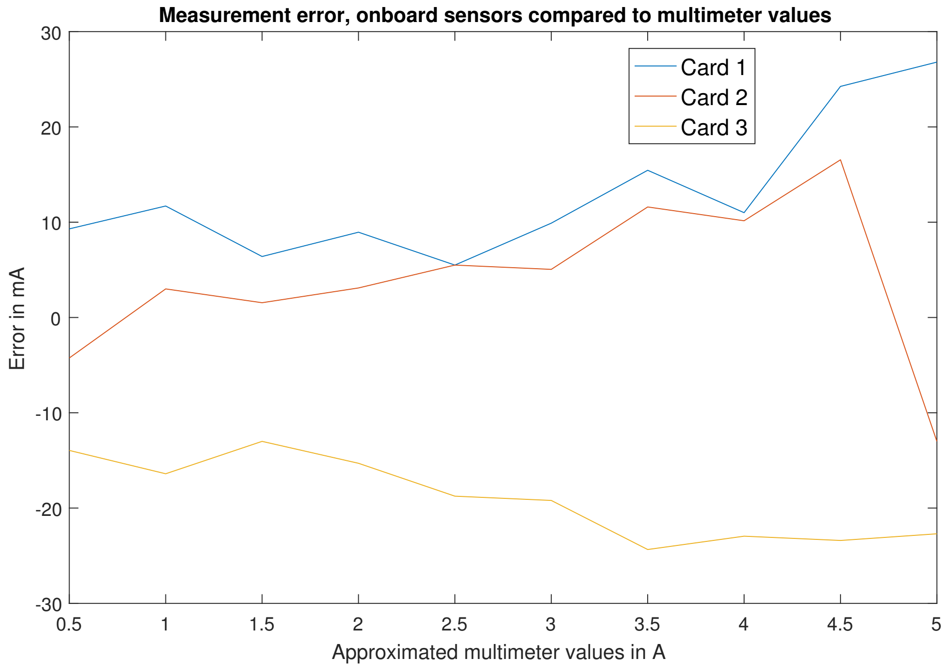

Figure 5.4: Measurement errors when comparing system sensors to multimeter values

The largest error detected in the current measurements compared to the multimeter is 25.9 mA. While being relatively accurate, it is not below 10 mA. The goal of an accuracy of 10 mA can therefore not be considered fulfilled.

5.2.3 Temperature sensor

The accuracy of the temperature sensors was tested by placing two cards in various places with different temperatures. A multimeter connected to a temperature probe was used as the reference. After two minutes time in that spot, the results were measured. The results are presented in Table 5.5.

Table 5.5: Temperature readings by Card 1-2 and a multimeter, test performed at four different ambient temperatures

Multimeter [°C]	Card 1 [°C]	Card 2 [°C]
0	0	1
19.2	19	19
22	22	23
23.5	24	24

To get an understanding of the temperature sensor's reaction time, the system and a multimeter temperature probe were both placed on the casing of a power resistor with a current flowing through it, effectively simulating a battery. The results of this test can be seen in Figure 5.5.

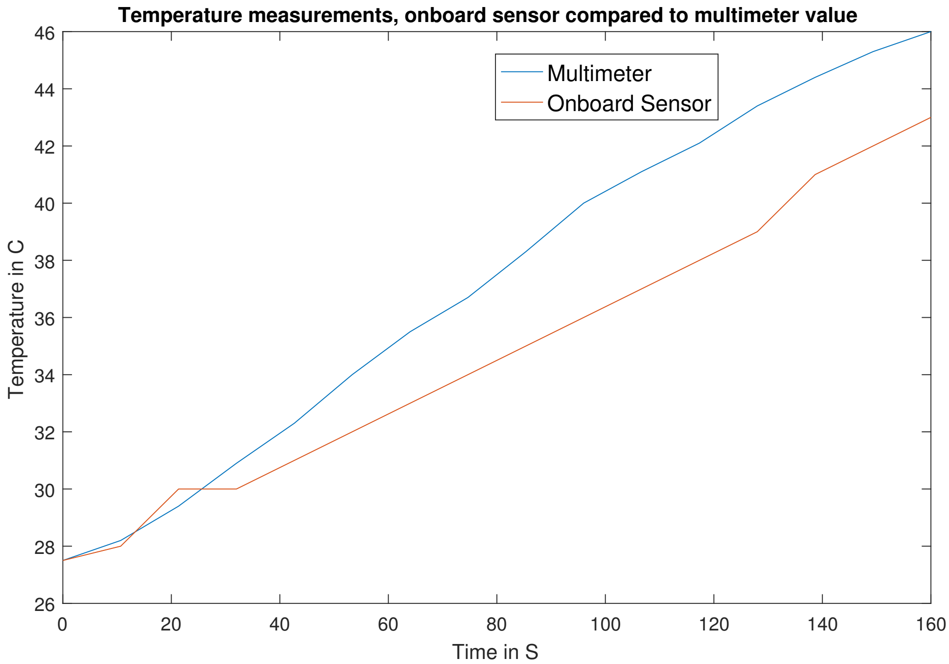

Figure 5.5: Temperature measurement with sensors physically connected to a heat source

These tests show that the temperature sensor is accurate down to 1°C when given time to rest, thereby fulfilling the goal of an accuracy of at least 1°C. If the temperature changes too quickly, however, this accuracy is lost.

5.2.4 Cost

The total cost for each system was 235 SEK. The largest single item in the system is the PCB itself, which accounts for 125 SEK of the total sum. The components mounted on the PCB together accounts for the last 110 SEK. This figure excludes the cost for mounting the components, since this was done by hand.

6
Discussion

In this chapter, the project results are analyzed and discussed. The research questions are discussed and answered combined with what significance each result has. A discussion of in which fields and applications this system, or the concepts of wireless BMS or distributed BMS in general, would be useful is also included. Finally, some key concepts and technologies that likely would improve the system if another future iteration of this product would be made are presented

6.1 Research question evaluation

In section 1.4, the research questions for this project are stated. In this section, the questions are discussed and answered based on the project results.

6.1.1 Communication without interference with 40 measuring units

The tests with 40 simulated systems resulted in a package receiving rate of 79% for the single send strategy and 64% for the double send strategy. While this result disproves the theoretical benefit from the double send protocol, it also proves that it is possible with receiving rates of 80% or more, which is deemed high enough for this project. Even if one in every five packages are lost, the rest of the data provides a good enough picture of the battery properties. Since there was no noticeable performance loss when strong Bluetooth and Wi-Fi signals, which are the most common sources of RF interference, the system is not prone to interference. The system also follows all the Swedish regulations regarding radio broadcasting.

Even though the theory suggested otherwise, the package receiving rate for the double send protocol was significantly lower than for the simpler single send protocol. This problem occurs because the total time to receive the package is longer than the actual package. The optimal protocol depends heavily on package length, where shorter packages benefit from the double send protocol while the longer packages work best with the single send protocol. The package receive time where the optimal protocol changes is 6.25 ms, as calculated in Equation 6.1.

$$\frac{x}{1000} \cdot 40 = (\frac{x}{500} \cdot 40)^2 \tag{6.1}$$

$$x = 6.25$$

The total time for the receiver to process each package is larger than the 6.25 ms threshold, which is why the package receiving rate is lower using the double send protocol. If more powerful receiver hardware running more optimized code would have been used instead, the package processing time would have been reduced, making the double send protocol beneficial for this application.

6.1.2 Benefits and drawbacks compared to commercial system

Compared to a standard BMS, as presented in Section 2.2.2, this design's distributed topology results in increased measuring accuracy, since every cell is measured individually. The increased accuracy results in a battery pack that is safer while also having a higher charge capacity. A distributed system also allows for increased modularity, since swapping cells, adding cells or removing cells becomes easier. The modularity is increased further by the wireless communication setup, since cells no longer have to be physically connected to the central unit. The lack of cables also reduces product size and weight, while also making it less prone to electrical failures.

Drawbacks compared to the commercial systems include a more complex system, which requires more hardware to function. The additional hardware requirements in turn results in a higher price per monitored cell. The wireless setup makes the system prone to interference and security breaches. Since radio space is limited, it also has a relatively low maximum number of units.

6.1.3 Economic viability

The total cost of each system was 235 SEK, which is higher than commercial alternatives and also higher than anticipated. The high price is a result of the low number of systems built. When ordering PCB manufacturing, there is a large initial cost to begin production, with additional cards only costing slightly more. The same goes for the components, where small quantities increases the price significantly.

If components and PCBs for 10000 systems instead would have been ordered, the price per unit could have been divided roughly by 3, resulting in a total unit price of around 60 SEK. In a product, this cost would be a significant part of the total battery pack cost. If the system is economically viable or not therefore depends on the application.

In applications with few cells but still a high unit price, such as drones, a system like this would be viable economically. The extra cost of a more advanced system would not be a significant part of the total price, but the increased accuracy and reduced size would be beneficial. In larger applications with a high number of cells, such as an electric car, the reduced size and weight of the system would be less impactful. The total cost for the system would also be significantly higher, as cost scales linearly with number of cells.

Depending on the application, the system could be modified to reduce cost. With some minor hardware modifications, one system could be used to monitor several cells. Sensors would still be mounted on every cell to maintain the accuracy, but not every cell would transmit the results individually. A setup like this would however slightly limit the modularity potential, since batteries now must be added or replaced in groups. The cost per cell could in the optimal case be halved, or reduced even further if more cells are connected together.

6.1.4 Power consumption

To be useful in applications, the system cannot consume too much power from the battery it is monitoring. The limits were set to 0.7 mW when not active and 1% of total power from the battery when active.

When active, the results show that the system consumes less than 1% of the total power at any input current. This means that the system, when active, will not significantly affect the product's battery time. When inactive, the system cannot be configured to draw less than 0.7 mW. Even if transmissions are turned off completely, the total power consumption of the components is higher than the 0.7 mW threshold.

6.2 Discovered problems

When testing the system, some of the results were worse than initially expected. In this section, the problematic results and the reason behind them are analyzed and discussed. Potential alternatives and solutions to the problems are also included.

6.2.1 Short range and packet losses

The systems communication range is very limited, with a maximum range of only a few centimeters rather than meters, as intended. This is due to the antenna, which ended up not being properly impedance matched for maximum transmission strength. The component intended for this purpose, the balun, proved to be physically too small to manually mount, which lead to it being skipped. This in turn causes an antenna that cannot transmit at full signal strength, resulting in packet losses and the limited transmission range.

At the time of the design choice including the balun, it was not fully decided on whether the system should be able to receive signals or not. If the decision for the system to only transmit signals would have been made earlier, the balun in its entirety could have been skipped, with the impedance matching instead being done with simpler components. Another option would have been to send the systems for professional mounting. This would have guaranteed that the balun would have be mounted properly, but at a significantly higher cost and increased lead time.

6.2.2 Low accuracy in current measurements

The largest detected error in the current measurements is 25.9 mA, more than twice the predefined maximum error of 10 mA. This is due to the shunt resistor used for measuring, which has a resistance error of $\pm 1\%$. This small error is then amplified 200 times within the amplifier, resulting in a larger error than initially expected. At a current of 5 A, it could create a maximum error of up to 50 mA. The move to a more accurate shunt resistor, for example one with $\pm 0.1\%$ error, would reduce the maximum error to 5 mA. It would also increase the total system price significantly, as high precision shunt resistors are expensive. Since every shunt resistor has a different error, a general software correction could not be implemented to correct it. It could be corrected by manually calibrating every system, but would be unpractical.

6.2.3 Slow reacting temperature sensor

The temperature sensor, while being accurate, tracks temperature changes slowly. This is due to the physical distance between the sensor and the battery and poor heat conductivity due to the sensor being embedded within the MCU. This means that the temperature sensor can detect if the surrounding temperature is suitable for battery use or not, but that it cannot be relied upon to detect battery problems such as short circuits which will cause rapid changes in temperature.

Instead of using the internal temperature sensor, a dedicated external sensor mounted directly on the battery could have been used. This would have allowed for faster reactions to temperature changes, but would also have increased the system cost and size.

6.3 Method evaluation

The method used for this project was designed so all deadlines could be met without delay. Since all of the deadlines were met without any significant delay, the method is considered successful. However, some quality issues were detected along the way which the method did not take into account. Due to long lead times for PCB manufacturing, each sensor setup and the communication setup could not be set up and tested individually before the final design decisions were made and the PCB was ordered. If given more time, this is something that should be added to the method.

6.4 Possible implementations

The distributed and wireless battery concepts open up many possibilities to improve battery usage, both as stand alone concepts and combined, as in this project. By adding these features, the battery manufacturer would have a product that is both more versatile and intelligent. It would also mean that each end user no longer would have to develop or acquire separate BMS solutions, since it is already integrated within the battery.

The main advantage of having a distributed system is the modularity it allows. Instead of adding or removing batteries in larger groups, the individual sensoring allows for the addition or removing of single cells. This means that excess space within devices now simply can be used for small amount of additional battery cells. It also allows for increased mass production of BMS systems, since each BMS solution no longer must be custom build for the application if every single cell has the same capability.

Measurements on every single cell also means that every single cell can be utilized fully, leading to longer battery lifetime and increased safety. This would be useful in applications where weight and size are limiting factors and all extra battery capacity is highly necessary, such as drones. The additional safety guarantees safe working conditions for the batteries, which is extra crucial in critical applications or hazardous environments, where an explosion or a fire would be disastrous.

The ability to communicate wirelessly with each battery has many obvious and some not so obvious potential benefits. The lack of a physical data wire allows the system to be both lighter and smaller. This is especially notable in applications where the batteries are spread out over the entire device due to for example weight distribution reasons. The many cables needed for a wired setup adds extra weight, size and reliability concerns, since cables can break if the device is bumped, shaken or otherwise mistreated.

Another less apparent use of wireless batteries is to communicate battery status of common household objects. A common household today has many battery powered devices, such as remotes, fire alarms and clocks, but for most of these there is no reliable way to determine the remaining charge. If all the batteries would have wireless communication, they could report the battery status occasionally to for example a mobile app, giving the user full control over every battery within the household.

6.5 Future project improvements

Neither the communication or the hardware design are flawless. For a future iteration of this project, five concepts would be interesting to research further and potentially implement to achieve better results. These concepts mainly address package receiving rate for the communication and power consumption on the hardware side, but also the concept of each unit transmitting the actual battery status instead of the measured data.

6.5.1 Communication

Instead of all the system communicating on exactly the same frequency, support for several different 868 MHz channels could be implemented. This would allow multiple systems to transmit simultaneously without interference. The SPIRIT1 already used in the system has support for several different communication channels, however a narrow hardware filter must be inserted into the design to distinguish between the different channels.

Another way to reduce the number of package collisions would be to instead design the cards to act as a transceiver rather than a transmitter. If each system can listen on the specified frequency, it allows them to only transmit when no other system is transmitting already, greatly reducing the risk of collision. The SPIRIT1 radio chip already supports this feature, but the systems lack of receiving capabilities currently prevents it from being implemented. A balun which balances the incoming radio signals from the antenna would be necessary to receive signals with the current system.

6.5.2 Reduced power loss

When it comes to power consumption, there are two parts contributing that can be divided into loss from passive and active components. Passive power loss occurs mainly in the voltage divider, shunt resistor and the antenna. To minimize the passive losses, a transistor could be added in front of the voltage divider. This would allow the system to only turn on the voltage divider when measurements are taken, thereby reducing the passive losses within the divider significantly. The shunt resistance could also be reduced, which would impact the power consumption mainly when the current is high. The third passive improvement would be to make a more accurate impedance matching of the RF and the filter, thus increasing efficiency. The total power sent to the antenna could then be reduced and still maintain the same transmission range

Currently, the MCU used is significantly more powerful than necessary. A smaller MCU with only the bare essentials would certainly be a good step towards lower power consumption, but would require more specialized code. Introducing a more effective sleep mode for when the system is in storage would potentially increase shelf life. An example of this would be to turn off the entire system when not in use and then have a current sensor wake the system up when it is put into use, effectively eliminating all losses when the system is not in use.

6.5.3 Transmitting battery status

In the delimitations it is stated that no State of Health or State of Charge algorithms are to be implemented. This is however something that could ease both the wireless communication as well as the systems versatility when implementing it into applications.

In the current configuration, a majority of the system's processing power is left unused. It would therefore be possible to implement these algorithms directly on each distributed system and calculate the battery status within each system. This would then give rise to several possible improvements. With the battery status known, each system could now be instructed to only relay information when any status deviation occurs, significantly reducing the number of packages sent. It would also mean that the total length of the package could be shorter, increasing the total number of potential transmitter units and reducing power consumption.

7
Conclusion

It is clear that the concept of distributed wireless BMS has great potential and could improve many battery using applications. The distributed topology allows for increased modularity and accuracy, resulting in higher battery capacity and safety, while the wireless communication technology can reduce the system size, weight and fragility. Disadvantages with the concept include a higher system price due to the need of more hardware and various wireless communication issues. Interference from other devices could limit performance and the wireless signals could be hijacked with the intent to damage the system. Due to a limited radio space, a relatively low maximum number of units can be connected simultaneously without package losses.

The resulting larger battery capacity is beneficial in any application that uses battery power. However, due to the higher price, it is most suitable for applications where the battery cost is low relative to the product and the number of batteries is relatively low. The wireless communication also works best when the number of battery cells is kept relatively low. Wirelessly communicating batteries could also be useful in normal households, where everyday objects such as remotes or fire alarms occasionally could communicate their battery status, giving the user full control of all batteries at all times.

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A

Appendix 1

Table A.1: Voltage measurements comparing reported sensor values to voltage read by a Keysight U1272A multimeter. Card 1.

Multimeter [mV]	**PCB [mV]**	**Error [mV]**
2505	2498	-7
2706	2690	-16
2900	2886	-14
3100	3086	-14
3306	3290	-16
3503	3484	-19
3707	3690	-17
3901	3882	-19
4101	4084	-17
4301	4280	-21

Table A.2: Voltage measurements comparing reported sensor values to voltage read by a Keysight U1272A multimeter. Card 2.

Multimeter [mV]	**PCB [mV]**	**Error [mV]**
2501	2496	-5
2697	2688	-9
2896	2890	-6
3100	3090	-10
3300	3299	-1
3500	3494	-6
3696	3688	-8
3896	3886	-10
4097	4094	-3
4304	4292	-11

Table A.4: Current measurements comparing reported sensor values to voltage read by a Keysight U1272A multimeter. Card 1.

Multimeter [mA]	PCB [mA]	Error [mA]
2505	2498	4
2706	2690	-5
2900	2886	-3
3100	3086	-3
3306	3290	-5
3506	3484	-8
3707	3690	-6
3901	3882	-8
4101	4084	-6
4301	4280	-10

Table A.5: Current measurements comparing reported sensor values to voltage read by a Keysight U1272A multimeter. Card 2.

Multimeter [mA]	PCB [mA]	Error [mA]
2501	2496	6
2697	2688	2
2896	2890	5
3090	3090	1
3299	3299	10
3494	3494	5
3688	3688	3
3886	3886	1
4094	4094	8
4292	4292	0

Table A.3: Voltage measurements comparing reported sensor values to voltage read by a Keysight U1272A multimeter. Card 3.

Multimeter [mV]	PCB [mV]	Error [mV]
2502	2494	-8
2698	2690	-8
2898	2890	-8
3101	3094	-7
3300	3294	-6
3501	3490	-11
3697	3688	-9
3899	3886	-13
4098	4088	-10
4305	4294	-11

Table A.6: Current measurements comparing reported sensor values to voltage read by a Keysight U1272A multimeter. Card 3.

Multimeter [mA]	**PCB [mA]**	**Error [mA]**
2502	2494	3
2698	2690	3
2898	2890	3
3101	3094	4
3300	3294	5
3501	3490	0
3697	3688	2
3899	3886	-2
4098	4088	1
4305	4294	0

Table A.7: Temperature measurement comparison between temperature probe from a Keysight U1272A multimeter and the onboard temperature sensor.

Multimeter [$^\circ$C]	**Onboard sensor [$^\circ$C]**
27.5	27.5
28.2	28
29,4	30
30.9	31
32.3	32
34	33
35.5	34
36.7	35
38.3	36
40	37
41.1	38
42.1	39
43.3	41
44.4	42
45.3	43

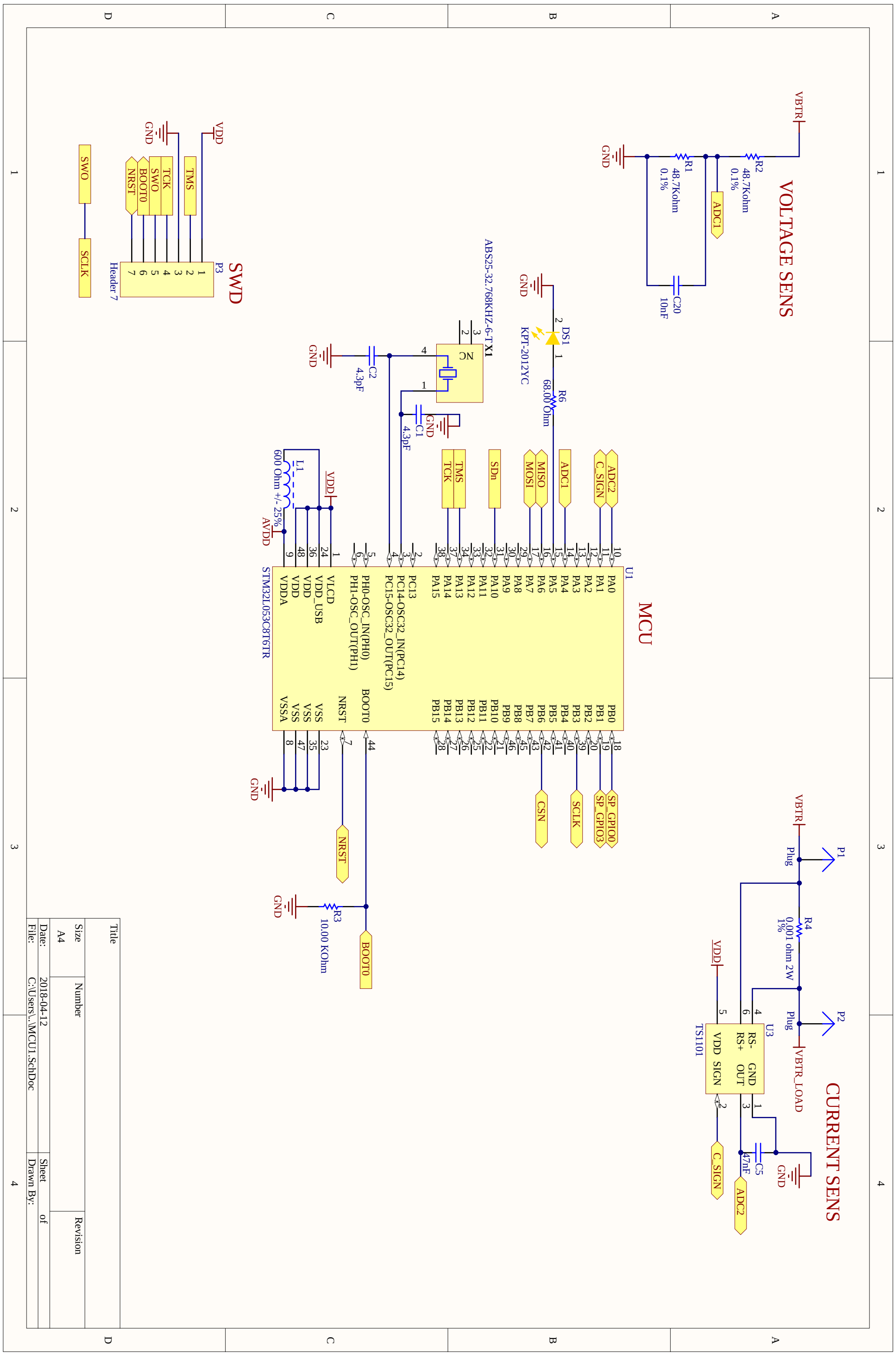

Figure A.1: Schematic over the microcontroller STM32l053 and current sensor TS1101, with SWD representing the pins for external communication

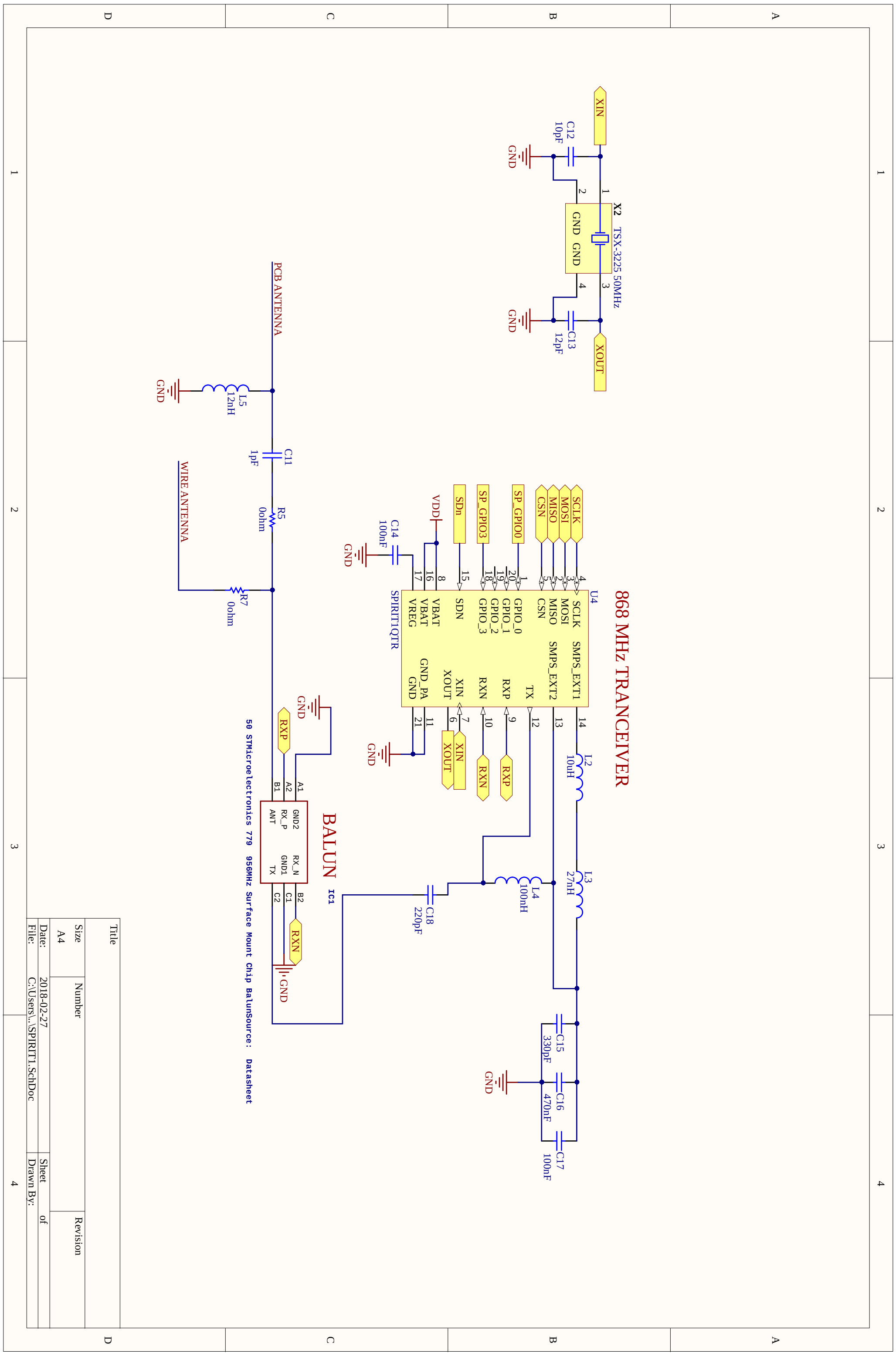

Figure A.2: Schematic of the wireless communications part of the system, centered around the SPIRIT1 chip

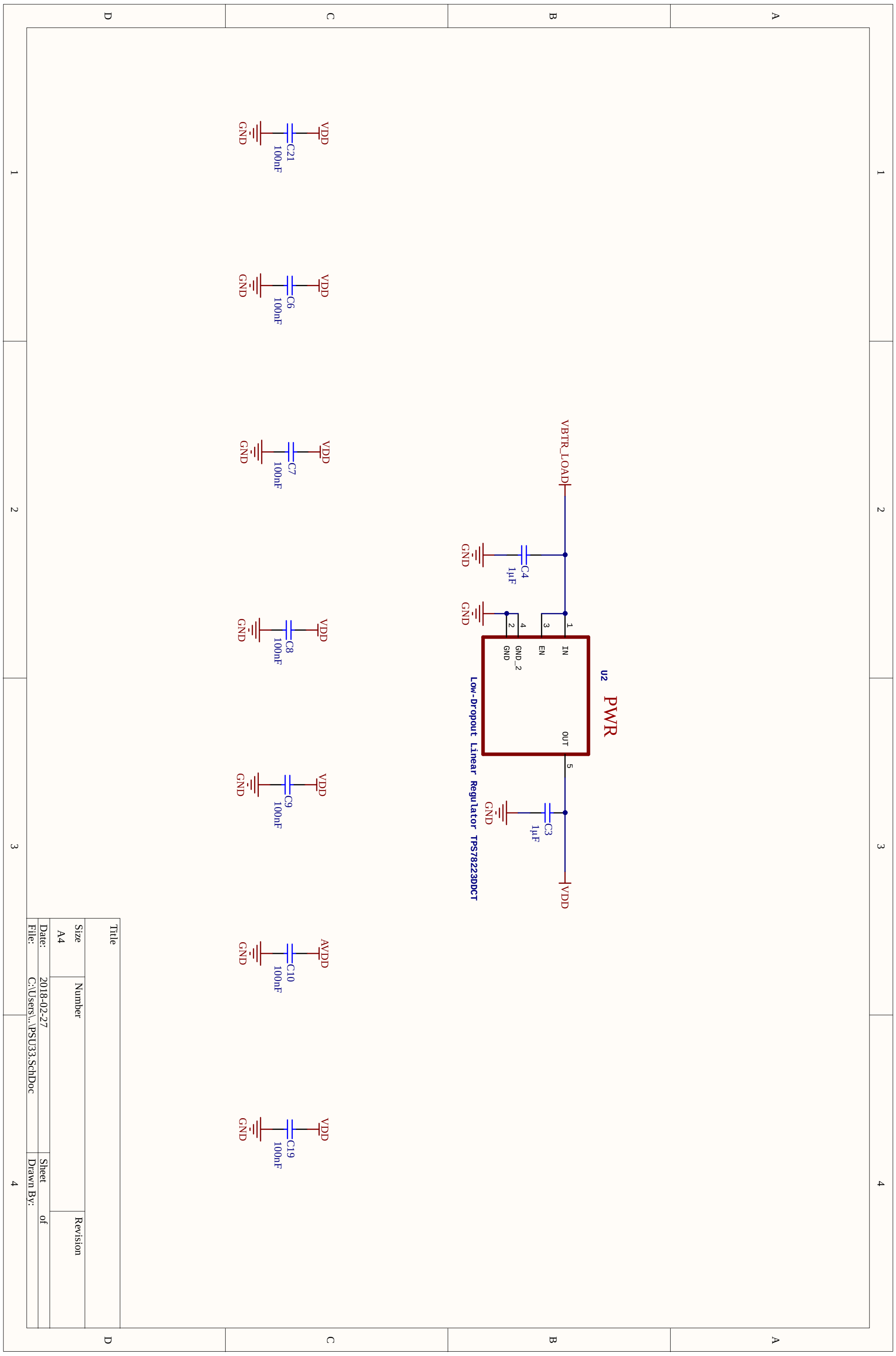

Figure A.3: Schematic over the power supply, 2.5-4.2 V battery voltage is converted down to 2.3 V

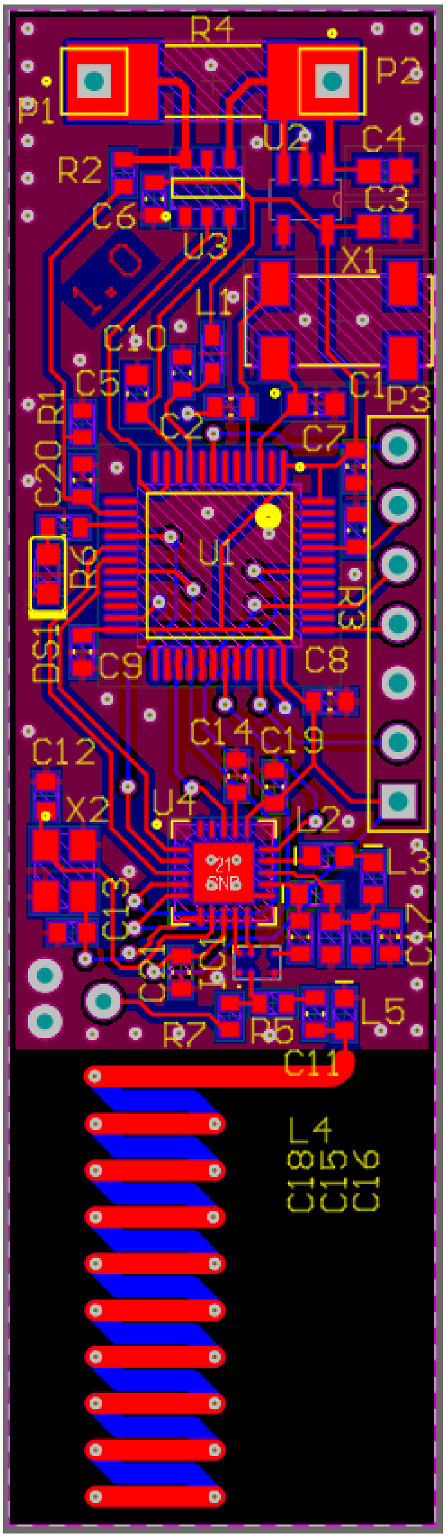

Figure A.4: PCB layout for manufacturing, red represents copper on top layer while blue is copper on bottom layer

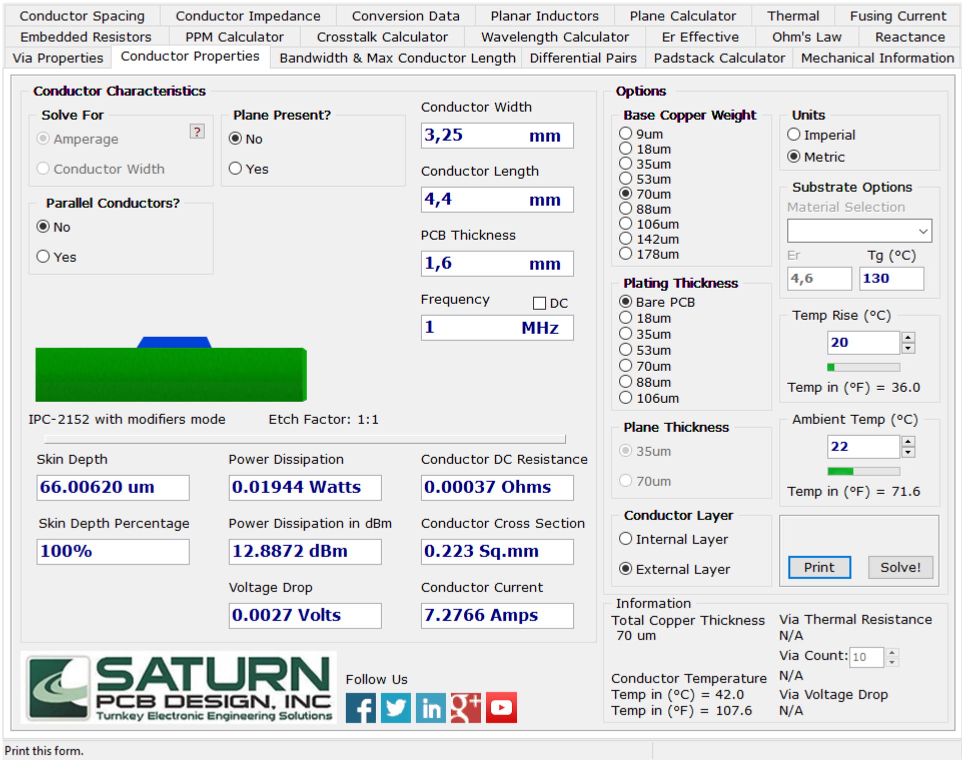

Figure A.5: Current calculations for only PCB trace without top solder. Allowed temperature rise at 20 C°

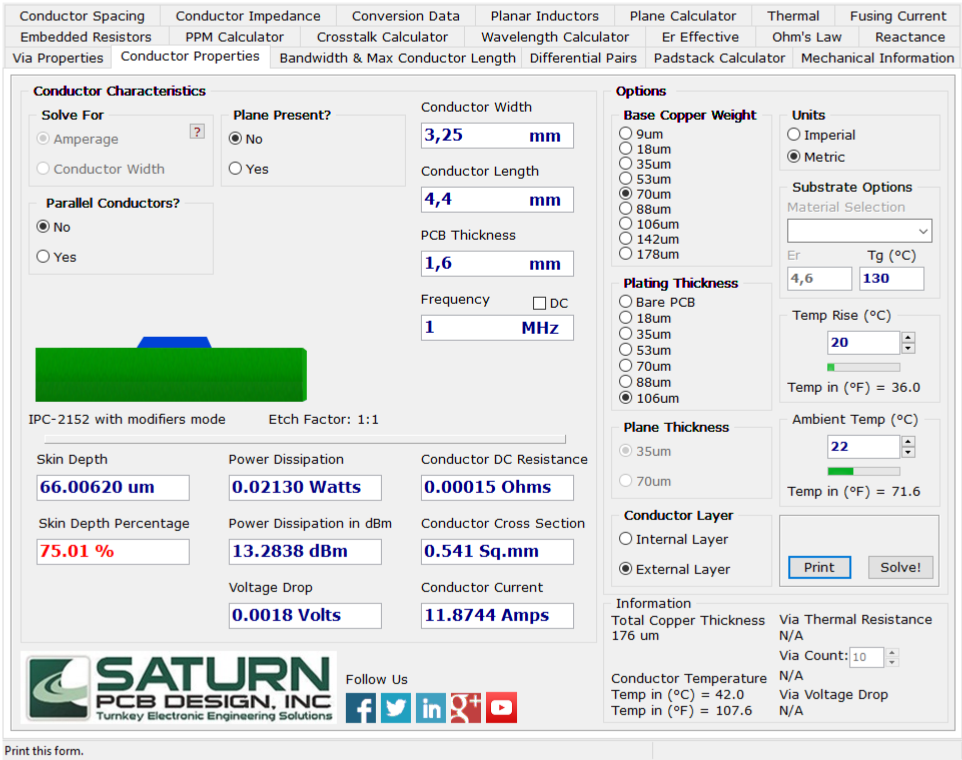

Figure A.6: Current calculations for only PCB trace with top solder of 106 μm. Allowed temperature rise at 20 C°