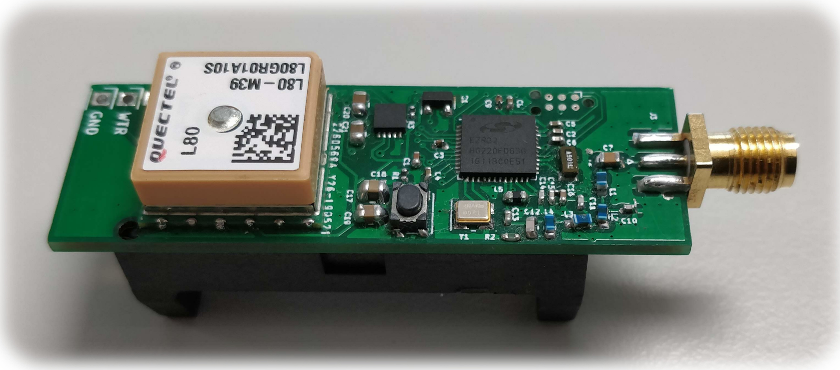
Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electronic Systems

Amund Askeland

Design of low power emergency beacon for life jacket integration

Master's thesis in ELSYS
Supervisor: Egil Eide
July 2019



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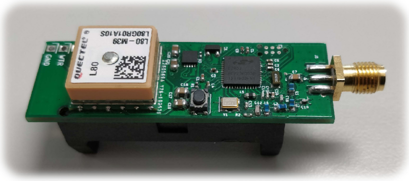

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Assignment

The following paragraphs are a translated version of the original problem description from AISTech AS:

Emergency Man Over Board (MOB) beacons for AIS is available from several manufacturers. The problem with these products is that they often interfere with the work performed by personnel on board ships or in floating fish farms. Since many of these devices are activated when a soluble tablet touches water, they are also prone to be activated from rain or water splash.

To solve some of these problems, it is desirable to integrate the MOB beacon into the life jacket. The final solution should be entirely concealed, and not be in the way of the user during normal work activities. Close cooperation with a manufacturer of life jackets is key to achieving good integration.

A fully integrated solution, where the antenna is integrated into the life jacket, represents a challenge with respect to antenna design and radiated power. A compromise could, therefore, be to design an antenna solution which is normally integrated into the life jacket, but where the can be deployed to give the required efficiency.

In short, the task is to design an AIS MOB device that can be fully integrated into a life jacket. The solution could be based around an AIS chip from CML, that contains the necessary elements to generate AIS signals. In addition, a processor solution is required to generate AIS MOB messages, and a power amplifier is required to achieve the required output power. It is also desirable to have a GPS receiver so that the MOB device can send its position.

The main elements of the task are:

- Describe the details of AIS MOB beacons in the AIS system
- Discuss a technical solution for an AIS MOB beacon based around the CMX7045 Marine SART processor from CML microcircuits
- Discuss design for integration in a life jacket, especially with respect to the antenna
- Calculate the range for the solution
- Create a prototype that can be measured and tested

Abstract

Man overboard (MOB) devices for use with the automatic identification system (AIS) has been commercially available for several years. These devices represent an important safety improvement for personnel working in maritime environments, as they help locate personnel overboard quickly. Existing solutions are designed as separate devices fastened to a life jacket, which can represent a hindrance in the work tasks performed by the user. To improve this design, it is desirable to integrate the device into the life jacket itself. This work aims to enable such integration by discussing the challenges that this leads to, propose an improved design, and implement a prototype to quantify the improvements.

The main focus of this work is to reduce the size of AIS MOB devices, as this is key to enable integration in life jackets. A large contributing factor to the size of existing systems is found to be the battery packs, and a reduction in power consumption is therefore focused heavily on in this work.

A fully functional prototype of an AIS MOB beacon is designed and tested. The prototype showed a significant reduction in both size and power consumption when compared to existing solutions. Notably, the prototype has less than $\frac{1}{10}$ of the power consumption of another AIS MOB beacon design described in recent literature. Limitations with these comparisons and future work is also identified and discussed.

Sammendrag

Mann over bord (MOB) nødsendarar for bruk med det maritime automatiske idendifikasjonssystemet (AIS) vert i dag av levert av fleire produsentar. Slike nødsendarar fører til auka sikkerheit for personar som arbeider innanfor maritime neringar, ved at dei bidstår i rask lokasjon av personar over bord. Eksisterande løysingar er separate einingar som vert festa til flytevestar, noko som kan føre til plunder og heft i normale arbeidsoppgåver for brukaren. For å finne ei betre løysing er det ønskeleg å integrere slike nødsendarar i sjølve flytevesten. Dette arbeidet har som mål og tilrettelegge for slik integrasjon. For å oppnå dette vil utfordringane ein slik integrasjon fører til bli diskutert, eit forbedra design bli føreslått, og ein prototype vil bli laga for å kvantisere forbedringar.

Hovedfokuset med dette arbeidet er å redusere størrelsen på AIS MOB nødsendarar, sidan dette er naudsynt for å få til god integrasjon i flytevestar. Ein stor del av størrelsen i eksisterande produkt er batteripakkane som vert brukt. Redusert straumforbruk vert derfor hovedfokuset for å få ned størrelsen på slike produkt.

I dette arbeidet har det blitt utvikla og testa ein fungerande prototype av ein AIS MOB nødsendar. Prototypen hadde ein signifikant reduksjon i både størrelse og straumforbruk samanlikna med eksisterande løysingar. Samanlikna med ein AIS MOB nødsendar som nyleg vart designa i publisert litteratur, har denne prototypen $\frac{1}{10}$ av straumforbruket. Unøyaktigheitar i samanlikningane som er gjort, samt behov for vidare arbeid er også diskutert i dette arbeidet.

Preface

The system designed in this thesis could have taken many different directions regarding which parts it focuses on. I chose to focus on prototype development and low power consumption, as these are the areas that come naturally to me and my embedded systems specialisation. The task does, however, span over many different disciplines, and it was necessary to exit my technological comfort zone to make a functional prototype. The work done in this thesis has been a very good opportunity to get a better feel and understanding of RF design and digital communication. My original plan was to include the design of an antenna in this thesis. Several different designs were simulated, but I had to abandon this plan in order to finish the thesis on time. It is my impression that a good antenna design could be the basis of a thesis on its own.

During the design and debugging process, I have relied heavily upon many different open source projects. The open source community never cease to amaze me in the sheer number of useful tools that exist. I have especially relied on using tools in the GNU Radio toolkit, and a very impressive spectrum analysation tool called Inspectrum. A big thank you goes out to all the people that have been involved in developing these tools.

I would like to thank my supervisors, Egil Eide and Per Christian Berntsen. Egil has given me useful tips, and valuable feedback on the writing of the thesis. Per Christian was the one to come up with this task, which has proven very interesting. I would also like to thank Are Eiesland and Kristoffer Skjølseth. I have shared the same radio lab with Are and Kristoffer, and they have answered many questions of mine regarding RF design and the specifics of different instruments.

Contents

List of Abbreviations

AIS	Automatic Identification System
BT	Bandwith Time
CMOS	Complementary Metal-Oxide-Semiconductor
CRC	Cyclic Redundancy Check
EM0-EM4	Energy Mode 0-4
ETSI	European Telecommunications Standards Institute
FIR	Finite Impulse Response
FSK	Frequency Shift Keying
GPS	Global Positioning System
GMSK	Gaussian Minimum Shift Keying
ISI	Inter Symbol Interference
LED	Light Emitting Diode
MCU	Microcontroller Unit
MOB	Man OverBoard
MSK	Minimum Shift Keying
NRZI	Non Return to Zero Inverted
PA	Power Amplifier
RAM	Random Access Memory
SDR	Software Defined Radio
SMU	Source Measurement Unit
SOTDMA	Self Organized Time Division Multiple Access
TTFF	Time To First Fix
UTC	Coordinated Universal Time
VCO	Voltage Controlled Oscillator
VHF	Very High Frequency

Chapter 1

Introduction

1.1 Automatic identification system and man overboard devices

The Automatic Identification System (AIS) was developed as an international collaboration in the mid-90s to improve safety at sea. Ships fitted with AIS transponders broadcast their position and heading, as well as receiving this information from other ships. This improves situational awareness and has become an important tool in maritime activities. Tracking and displaying other ships is great for avoiding collisions and other dangerous situations, but in the beginning, AIS had no means to help personnel falling overboard. In recent years the AIS protocols have been extended to include distress messages that can be used by Man Over Board (MOB) devices. The concept behind MOB beacons is described in Figure 1.1. When such a device is activated, it will acquire its position by using the global positioning system (GPS) and send AIS messages to nearby ships notifying them of the situation. Personnel falling overboard from ships can be very hard to locate, and given that time in these situations are very limited, MOB devices can be the difference between life and death.

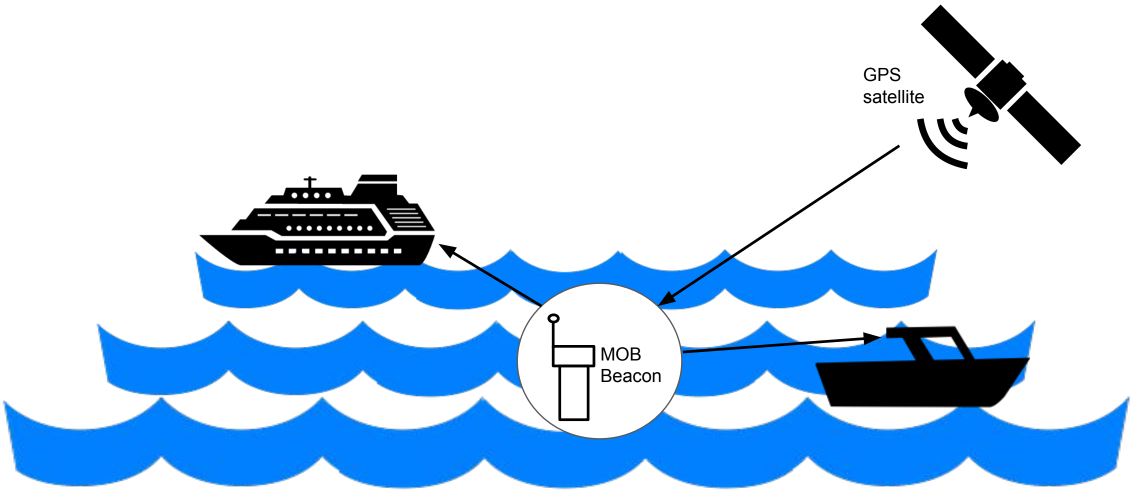


Figure 1.1: AIS MOB device concept

1.2 Problem Description

There are many commercially available AIS MOB devices, and most of them share the same basic design. They resemble a flashlight, that is fastened to the lifejacket of the user. When submerged in water the device activates and deploys some form of retractable antenna. The problem with these devices is their size and the way that they are fastened to the life jackets. These devices are almost exclusively used by personnel working in maritime environments, and the work is often of a physical nature. Modern self-inflatable life jackets have reduced the size of life jackets considerably, but hanging a flash-light-sized device on it can be a real hindrance and an annoying addition. Several examples of existing AIS MOB beacons are shown in Figure 1.2.

Figure 1.2: Mob beacons from various manufacturers, reproduced with permission from Panbo [1]

1.3 State of the art MOB devices

There are several commercially available AIS MOB devices from a range of manufacturers. Two such devices are the rescueME MOB1 from Ocean signal and the SafeLink R10 from Kannad marine. The SafeLink R10 can be seen in the middle of the figure 1.2. The rescueME MOB1 is currently marketed as *"The worlds smallest personal locating AIS Man OverBoard device with integrated DSC"* [2].

In addition to commercially available products, Y. Li et al. described the design of an AIS MOB device in a published article [3]. In that work, the authors state that an improvement with respect to operation time was achieved when compared to existing products. However, it does seem like the authors made an error, as they stated that the rescueME MOB1 has a battery capacity of 2400 mA h, while the actual value is 1500 mA h [4] [5]. It can, therefore, be argued that the increase in operation time achieved by Y. Li et al. is mostly due to an increase in battery capacity when compared with the rescueME MOB1. Table 1.1 compares some important parameters of existing products, with respect to size and power consumption.

Table 1.1: Comparison of existing work

	Y. li et al. [3]	**Ocean signal MOB1 [6]**	**Kannad R10 [7]**
Battery change cycle	-	7 years	7 years
Operation time	36 h	24 h	24 h
Battery voltage	6 V	6 V [4]	6 V
Battery capacity	2400 mAh	1500 mAh [5]	-
Active current draw	66.6 mA	-	-
Size	22X45X118 mm	27X38X134 mm	27X47X124 mm
Weight	100 g	92 g	120 g

1.4 Solution concept

By integrating the MOB device into a life jacket, the MOB device would no longer be a hindrance, and it would potentially result in increased usage of such devices. Designing an AIS MOB device is not trivial in the first place, additionally, several challenges need to be addressed to enable life jacket integration. The main problem is that the overall size has to be reduced. One of the main contributors to the size of these devices is the battery packs, so designing a smaller system translates into designing a system with lower power consumption. This work will focus on the design of a prototype of such a system, with the main goal of reducing the physical size and the power consumption of the system. A block diagram of the required components for such systems is shown in Figure 1.3. These components include a GPS module, a Microcontroller unit (MCU), a radio transmitter, and a power amplifier (PA).

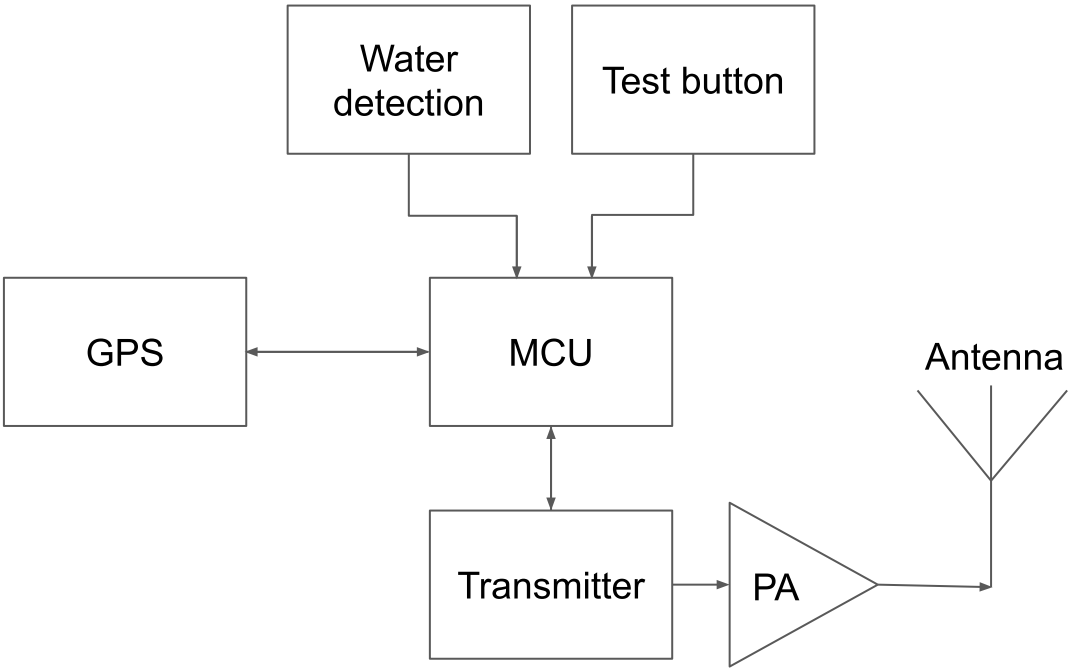


Figure 1.3: System block diagram

Designing the electronics of such a device is a multi-disciplinary task spanning over many disciplines including firmware design, digital communication, RF-circuitry design, antenna design, and low-power embedded design. In order to reduce the design time, not all parts of the system will be designed. The PA will be designed, but the main focus with this will be to achieve the correct output power, as this is necessary to get accurate comparisons with state of the art products. The antenna will not be designed, as this could represent a large workload. Instead, the output power and spectrum will be measured with lab-equipment, and antenna solutions will be discussed briefly.

Chapter 2

Background

Achieving low power consumption will be one of the main goals of this work. The goal of low power consumption will be second only to that of making a functioning system, as that will be crucial in order to make any meaningful comparisons with other work. This chapter will go over some important techniques for achieving low power consumption, as well as modulation methods and specifications related to AIS.

2.1 Low power design techniques

When designing low power embedded systems, a large part of the challenge with achieving low power consumption lies in the hands of the designers of the individual components. However, there is little use if the system designer cannot correctly utilise these components. In order to make the correct decisions on the system design level, it is important to have a good understanding of the power saving techniques implemented in the devices that make up the system. This chapter will take a look at common power saving techniques in MCUs, and the application level usage of these, as well as general system level power saving techniques.

2.1.1 Application level power saving techniques in MCUs

MCUs are good examples of devices where the designers implement a large number of power saving techniques, and where the application designer is often in charge of utilising these. Some of the most common power saving techniques in MCUs are based on the points listed below [8].

- Specific tasks can be performed with greater power efficiency and speed in dedicated hardware compared to general hardware
- The dynamic power consumption in CMOS devices are proportional to the square of the applied voltage and the frequency
- Unused parts of the system can be disabled by clock gating or power gating

In essence, MCUs are general computers that can run code written for them. But as the first bullet point from the above list states, specific tasks can be performed more efficiently by dedicated hardware. MCU designers address this by including specialised hardware peripherals in the design that can be controlled by the main computing unit of the MCU. Examples of peripherals include cryptography hardware, communication peripherals, and timers. To benefit from the peripherals, it is important that the application designer selects an MCU with the desired peripherals, and that these are utilised correctly.

The second bullet point is addressed by creating different voltage and frequency domains within the device. The voltages are not a concern for the end application designer as they are handled by the device itself. To get different frequency domains, it is common to use two different clock sources for the MCU. One frequency that is used as the main clock for computing usually running at several MHz, and a much lower frequency clock that can be used for timers and low-frequency peripherals often running at a few kHz. To further reduce power consumption these clock sources can often be reduced with frequency dividers. The selection of which frequency to run different peripherals at are often left to the application designer.

The final bullet point is about turning off unused parts of a system. Within MCUs this is often abstracted away by defining different power modes. These power modes represent different levels of power saving, where different levels of functionality are available. A common power mode is a mode where only a low-frequency timer is available. This mode is useful to use for periods when the MCU does not need to do any computations, but still needs to keep track of time, and possibly exit the low power mode after a certain amount of time has elapsed. A more aggressive kind of low power mode is one where no clock sources are active, and the system is only able to exit the low power mode on an external event such as the level shift of an external pin [9] [10] [11].

2.1.2 General power saving techniques on a system level

A large part of saving power on a system design level is done by selecting the correct components for the system. This especially applies to chipsets and other active components. While the obvious consideration is to select components that have the lowest power consumption by themselves, there are other important considerations like the operating voltage of the components. If different parts of the system operate at completely different voltages, regulators have to be introduced into the circuit. This leads to increased power consumption since no regulators have 100% efficiency. The added power consumption from regulators becomes increasingly important for systems with low power consumption, as regulators typically have lower efficiencies when their output current is small [12] [13]. For systems operating in a low power mode for most of the time, it is therefore beneficial to avoid the need of regulators for the components that need constant access to power. This is achieved by choosing a voltage source (e.g battery) that has a voltage output that can be directly utilised by these components.

Often active components in embedded systems are not used continuously. If the power consumption of the component while not being used is unacceptable, this can be battled by gating the power supply to the component. This can be useful for a range of components and subsystems, to minimise the consumption of the system. This gating of the power supply can be done with simple transistors, preferably with low on resistance.

2.2 Modulation

When transmitting data with radio waves, one often talks about the frequency at which the data is transmitted as a single value. However one cannot transmit any information in a signal with constant frequency and constant amplitude. Instead, modulation of a carrier wave is used. Modulation is the process of altering the amplitude, phase, or frequency of the carrier wave so that it can be used to send information.

2.2.1 Gaussian minimum shift keying

Frequency Shift Keying (FSK) is a modulation scheme where shifts in the frequency of the signal are used to encode data. An illustration of FSK modulation is shown in Figure 2.1. This figure also illustrates an important concept of continuous-phase. If an FSK signal does not have continuous-phase, the abrupt change in the signal introduces unwanted high-frequency components in the signal. These unwanted frequency components mean that the channel bandwidth increases, which can lead to interference with neighbouring channels.

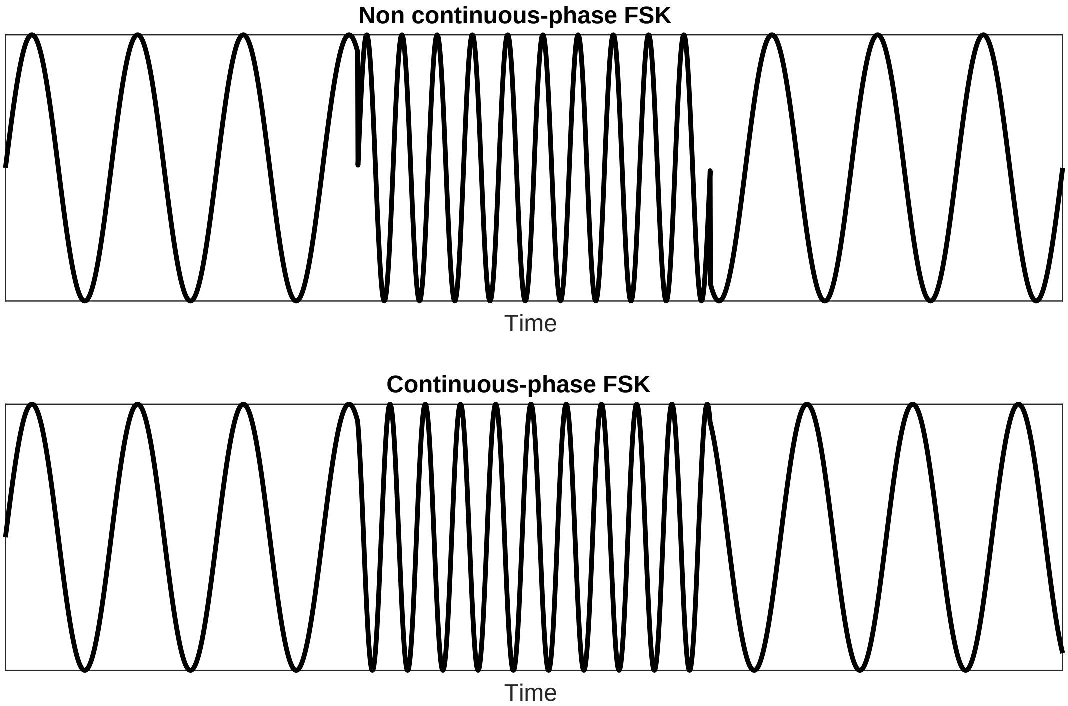


Figure 2.1: FSK modulation with and without continuous phase

Another important concept in digital communications is orthogonality. Two signals are said to be orthogonal when their correlation is zero. Correlation is, in essence, a measure of how closely two signals resemble each other and thus having orthogonal symbols help to distinguish them. For two continuous-time signals, $x(t)$ and $y(t)$, the correlation, $\langle x(t), y(t)\rangle$ can be written as below [14].

$$\langle x(t), y(t)\rangle = \int_{-\infty}^{\infty} x(t)y(t)^{*}dt$$

If two signals are orthogonal, they have to satisfy $\langle x(t), y(t)\rangle = 0$. In the case of FSK, it can be shown that the smallest symbol separation that satisfies orthogonality and phase-continuity is achieved when the symbols are separated by a frequency of $\frac{1}{2T_s}$, where T_s is the symbol duration. [14]. This is what's known as Minimum Shift Keying (MSK), which is a special case of FSK. One of the main advantages with MSK over many other modulation schemes is that it has a lower bandwidth for signals with the same symbol rate. It can be shown that MSK has a spectral density, $G(f)$, given by equation 2.2.1 [15].

$$\frac{G(f)}{T_s} = \frac{16}{\pi^2}\left(\frac{\cos(2\pi f T_s)}{1 - 16f^2T_s^2}\right)^2 \tag{2.2.1}$$

Even though MSK is designed with spectral efficiency in mind, sometimes it is desirable to reduce the bandwidth further. One technique that can be used, is to filter the MSK signal before modulation with a Gaussian filter. This is known as Gaussian Minimum Shift Keying (GMSK). This filtering causes the symbols to spread out in time, leading to the symbols no longer being orthogonal and causing inter-symbol interference (ISI). GMSK is, therefore, a trade-off between bandwidth and ISI. A Gaussian filter has an impulse response, $h_G(t)$, given by equation 2.2.2, and a transfer function, $H_G(f)$, given by equation 2.2.3. The parameter α is related to the 3 dB baseband bandwidth, B, of the transfer function by equation 2.2.4 [16].

$$h_G(t) = \frac{\sqrt{\pi}}{\alpha}\exp\left(-\frac{\pi^2}{\alpha^2}t^2\right) \tag{2.2.2}$$

$$H_G(f) = \exp(-\alpha^2 f^2) \tag{2.2.3}$$

$$\alpha = \frac{\sqrt{\ln(2)}}{\sqrt{2}\cdot B} \tag{2.2.4}$$

The GMSK premodulation filter can then be completely defined from B and the symbol duration T_s. This is usually referred to as the Bandwidth-Time product, or the BT-product. The spectral density of GMSK can be found by combining equations 2.2.3 and 2.2.1. Figure 2.2 shows a comparison of the spectral power of MSK and GMSK with different Gaussian filters. Smaller values of BT leads to smaller bandwidths, at the expense of increased ISI.

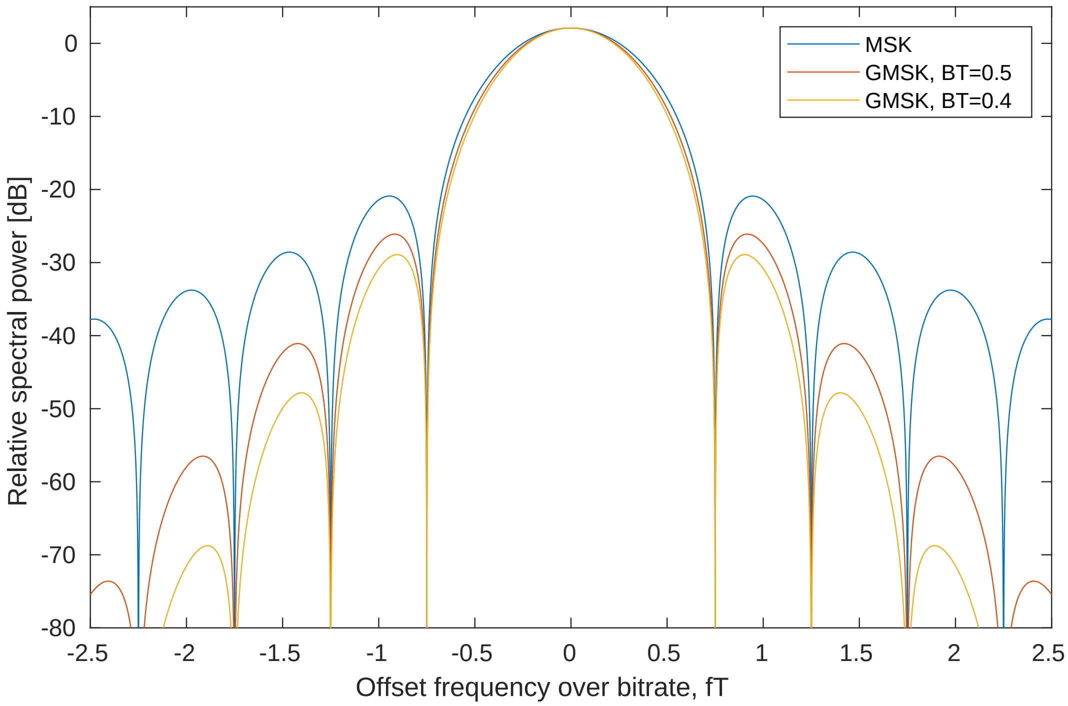


Figure 2.2: Spectral density comparison of MSK and GMSK

2.3 AIS specifications

2.3.1 Physical layer

AIS operates on two channels in the very high frequency (VHF) band, referred to as AIS channel 1 and 2. The centre frequencies for these channels are respectively 161.975 MHz and 162.025 MHz, and the channel spacing is 25 kHz. AIS messages are transmitted using GMSK modulation with two symbols. The BT-product of the pre-modulation filter is 0.4. The data rate used by AIS is 9600 bit/s and the frequency deviation is 2.4 kHz [17]. This satisfies GMSK modulation as discussed in Section 2.2.1.

Before the bitstream is GMSK modulated, Non-Return-to-Zero-Inverted encoding is applied. The NRZI encoding used by AIS encodes zeros as a level shift and ones as no level shift [17]. Figure 2.3 shows an example of this encoding scheme.

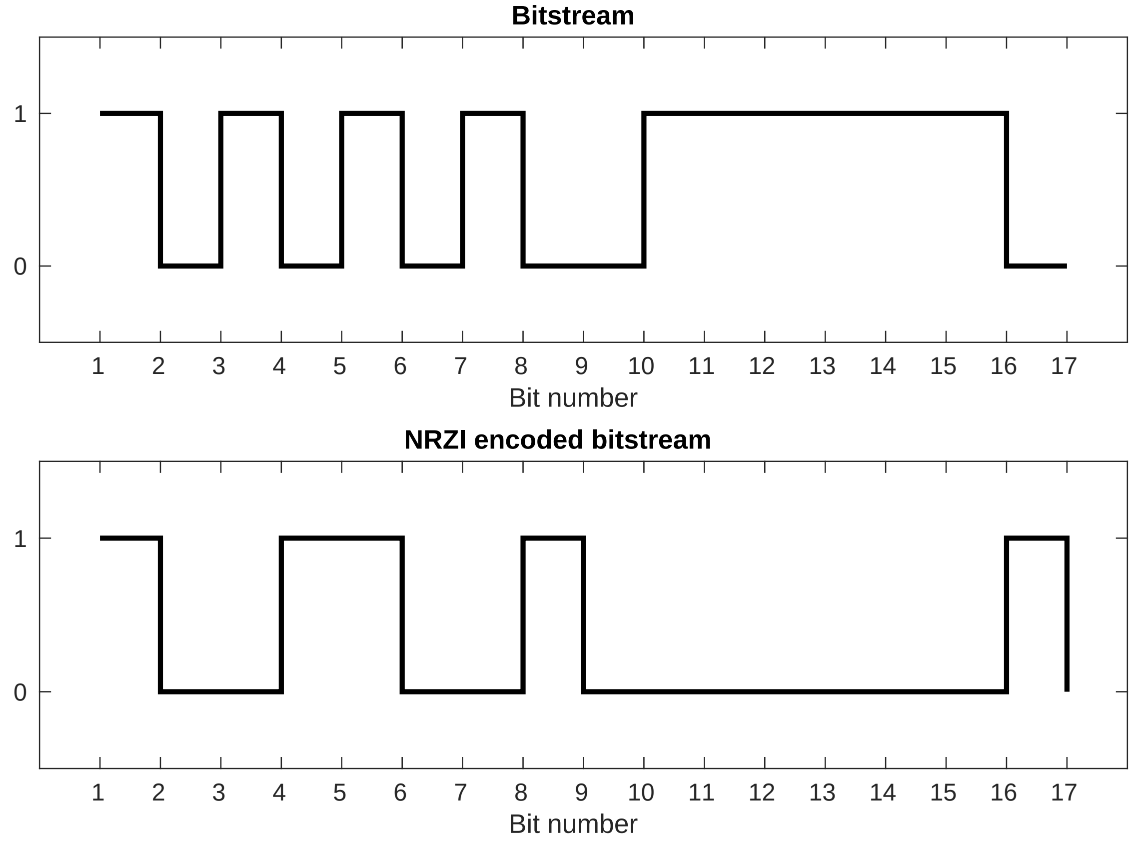


Figure 2.3: NRZI encoding

Figure 2.4 shows the spectrogram of a captured AIS message sent by a ship. This figure shows signal after it has been downmixed to baseband (i.e the carrier frequency has been subtracted). The lower graph shows the strongest frequency component over time and represents the NRZI encoded bitstream sent by the ship. The figure shows relatively smooth transitions between the two symbol frequencies, which is a result of the filtering in the GMSK modulation.

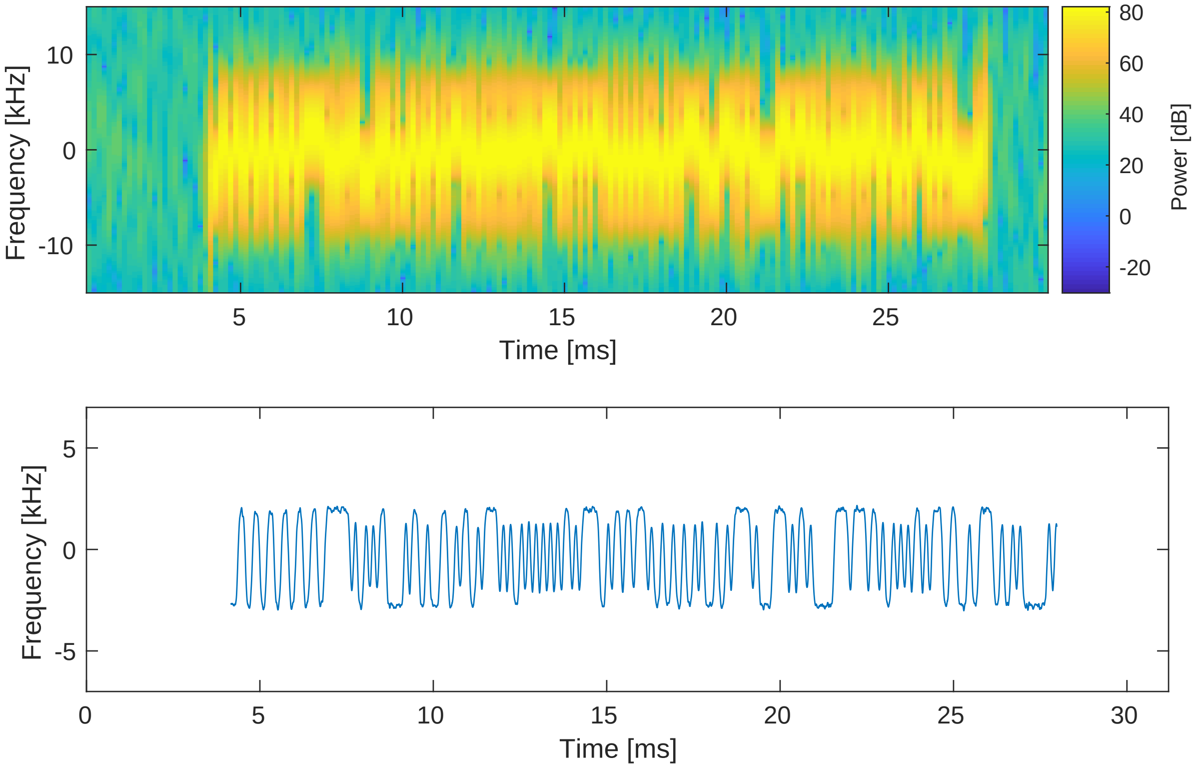
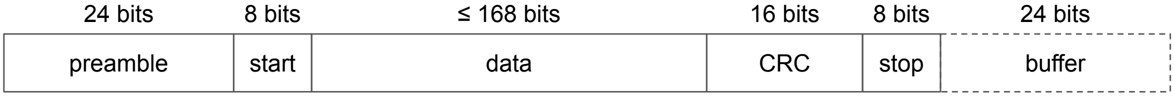


Figure 2.4: Captured AIS message from ship

2.3.2 Link layer

The AIS messages are build up as shown in Figure 2.5. The first 24 bits is a preamble, which is a series of alternating ones and zeros that can start with either a one or zero. The next field is an 8-bit start flag indicating the start of a message. The value of the start flag is 0x7E, or 01111110. The data field can have various length and is interpreted according to the AIS specification. After the data field, two bytes of Cyclic Redundancy Check (CRC) follows. The CRC value is calculated by performing the CRC-16-CCITT algorithm on the data field. This algorithm is described in ISO/IEC 3309. After the CRC field, there is a stop field indicating the end of a message. The stop field has the same value as the start field. By looking closely, and applying NRZI-encoding, one can identify the preamble, start and stop flag in the signal in Figure 2.4.

The last field shown in Figure 2.5 is a buffer which is not an actual field that is sent, but it serves several important purposes. These purposes include compensation for distance delay and synchronization jitter [17], as well as bit stuffing which will be explained below.



24 bits	8 bits	≤ 168 bits	16 bits	8 bits	24 bits
preamble	start	data	CRC	stop	buffer

Figure 2.5: AIS packet structure

The actual AIS messages that make up the data field, are organized into several different types such as position reports, base station reports, and safety-related messages. This work will use AIS message type 1, which is a scheduled position report, and message type 14 which is a safety-related broadcast message. The content of these messages are described in appendices A.1 and A.2 [17]. After the data field has been properly constructed, the CRC algorithm is performed and, the CRC field populated. One problem that might arise, is that the data and CRC fields might contain start or stop flags. This is solved by applying bit-stuffing, which is done by inserting an extra zero-bit after five consequent ones.

2.3.3 Time division

AIS uses self-organized time division multiple access (SOTDMA) to distribute access to the transfer medium (i.e the AIS channels) [17]. AIS uses a concept of frames lasting exactly one minute, starting on each minute boundary. Frames are divided into slots that have space for 256 bits of data, the AIS data rate of 9600 bit/s results in 2250 slots per frame. The key element of SOTDMA is that the transmitted messages contain information of the slots that the equipment intends to use in the future. This means that AIS equipment can use information from received messages to find a free slot where it can transmit. Devices that can transmit, but not receive messages, need to indicate this in the transmitted data. Such equipment should still indicate the next slot that it intends to use.

2.3.4 AIS MOB beacon requirements

AIS MOB beacons that wish to comply with regulatory standards, should follow a standard described by the European Telecommunications Standards Institute (ETSI) [18]. This standard specifies the way that MOB beacons should operate, as well as requirements regarding output spectrum and power.

2.3.4.1 Operation

Parts of the standard describes the way that the MOB beacon should operate, with respect to when and how it should send distress messages. Some of the most important points described in this standard include:

- Once a beacon has been activated, it shall start transmitting within 60 seconds
- If no position is available, a default position shall be used
- GPS position shall be acquired within 5 minutes. After the first position fix, the position should be updated every minute.
- UTC time acquired from the GPS shall be used to identify the start of frames.
- The equipment shall include a visible and/or audible indicator showing the status of the device.
- The equipment shall include a test mode, where AIS MOB test messages are sent to test the functionality of the device.

In order to increase the chance of distress messages being received, the actual transmissions should be done in bursts of eight messages. The messages in the bursts alternate on channel one and two, with 75 slots (two seconds) apart. These bursts should be sent one minute apart, and after eight bursts the next burst should start at a randomly selected slot 1 minute ± 6 s after the start of the previous burst. Figure 2.6 shows the burst operation of MOB devices.

In active mode, two messages of AIS type 14, with the text "MOB ACTIVE" should be sent every 4th minute, starting from the first minute. These messages should be the 5th and 6th messages within the burst. The other messages should be AIS type 1, containing the position of the device. The details of the content in these messages are described in appendix A.2 and A.1 [17].

In test mode, only one burst should be sent. Here the 1st and the 8th message should be AIS type 14 with the text "MOB TEST", and the remaining messages should be AIS type 1.

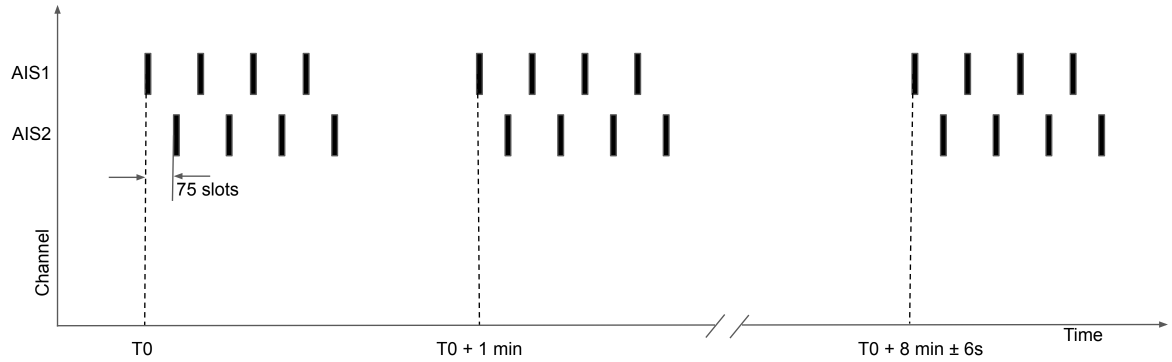


Figure 2.6: AIS MOB burst operation, adapted from [18]

2.3.4.2 Output spectrum and power

The ETSI regulatory standard sets limits on the effective radiated power (ERP) to 600 mW ± 3 dB. Spurious emissions are limited to 25 µW in the ranges 108 MHz to 137 MHz, 156 MHz to 161.5 MHz, and 1 525 MHz to 1 610 MHz [18].

The standard also describes a near spectrum mask that limits on the output spectrum of AIS MOB devices close to the carrier frequencies. This mask defines limits to the output power between -62.5 and 62.6 kHz carrier offset [18]. The values of the mask are referenced to the strongest frequency component. The mask can be seen in figure 2.7.

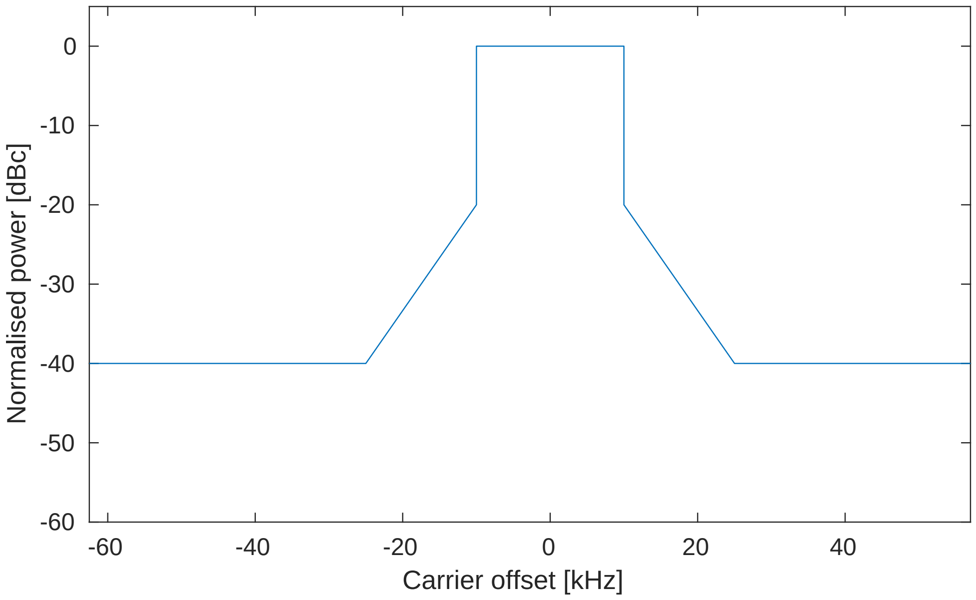


Figure 2.7: AIS MOB spectrum mask [18]

Chapter 3

System design plan

When designing an embedded system, it is important to have a clear understanding of the performance requirements of the system. The AIS specification imposes some timing requirements on this system, but those are not very strict. The requirement that will be the main focus, is that the entire system should be small enough to be easily integrated into an inflatable life-jacket. This one requirement leads to quite strict power consumption requirements, as there is less space for the battery. Also, reducing the number (and size) for the components used will be desirable. The requirements are summed up in the list below, as one can see some of the requirements are more concrete than others.

- Capable of transmitting with an ERP of 600 mW ± 3 dB
- Battery lifetime of 24 hours when continuously active
- Battery change cycle of at least 5 years
- Small enough to be completely integrated into a life jacket
- Ability to detect that the user has fallen into the water
- Ability to start a test of the device from the push of a button
- Ability to acquire coordinates within a reasonable time

Having these requirements identified before designing the system helps making sure that good design choices can be made.

3.1 System overview

The high-level block diagram from the introduction identifies the components required in this design. The same diagram is shown in figure 3.1. The MCU sits at the heart of the system and will be controlling the rest of the system. The MCU also needs to be able to generate the correct content of AIS messages. The GPS module is used to acquire the position of the device. The transmitter needs to be capable of receiving commands from the MCU and generating correct RF signals based on those commands. The PA is used to achieve the desired output power. Means of detecting water and a test button is also required to initiate the system. Each of the blocks will be looked into in more depth to determine the components that will be used.

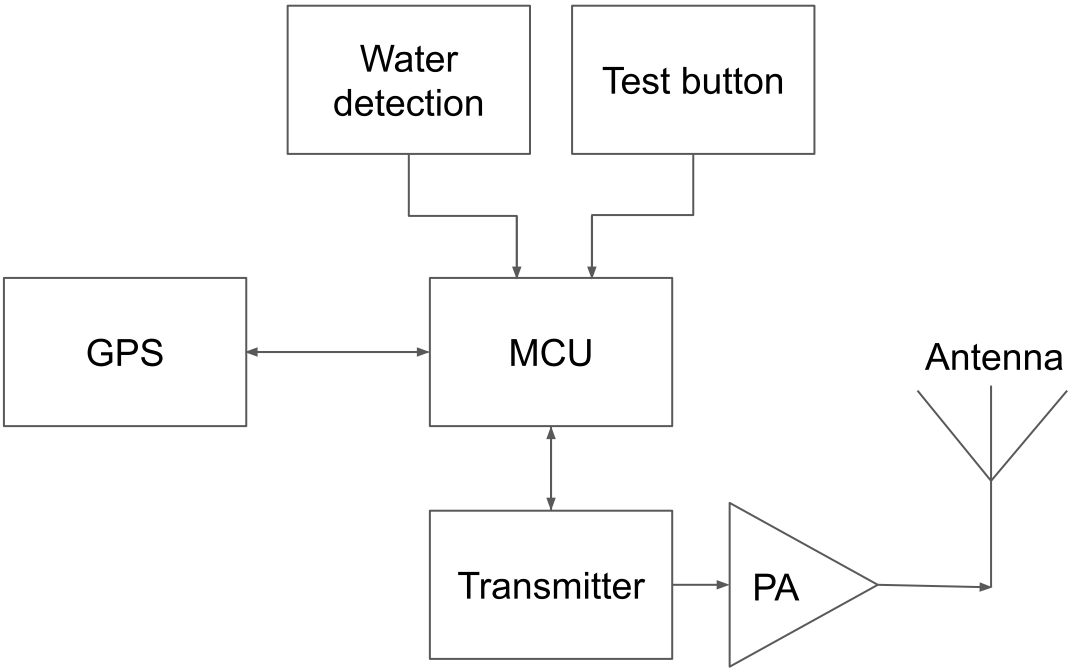


Figure 3.1: System block diagram

3.2 Component selection

While the necessary modules are described in Figure 3.1, choices for the actual components are still to be made. This section will discuss the choices for the actual components used. The goal of this section is to select the main components like the MCU, GPS, and transmitter. Passive components like capacitors, inductors and resistors will naturally not be part of this selection. When selecting components, the main considerations will be to keep the design time, power consumption, and system complexity low.

3.2.1 Transmitter

To the author's knowledge, the only company producing dedicated MOB processors is CML Microcircuits. CMX7045 is such a device that implements parts of the AIS stack, and it is compliant with the applicable standards. This device can take simple commands from a host MCU, and generate a modulation signal. This device might seem like a perfect fit for this system, but there are some drawbacks. First of all, this is not really a transmitter. The CMX7045 generates a modulation signal, that has to be mixed together with a carrier frequency to generate the desired RF signal. This raises the need for an additional component in the system, as shown in Figure 3.2 CML Microcircuits proposes to use a voltage controlled oscillator (VCO) to achieve this. The device also operates in a high and narrow voltage range of 3.0-3.6 V compared to most modern silicon devices. Furthermore, the current draw of the device when inactive (deep sleep) is listed as 28 µA which is comparatively high [19].

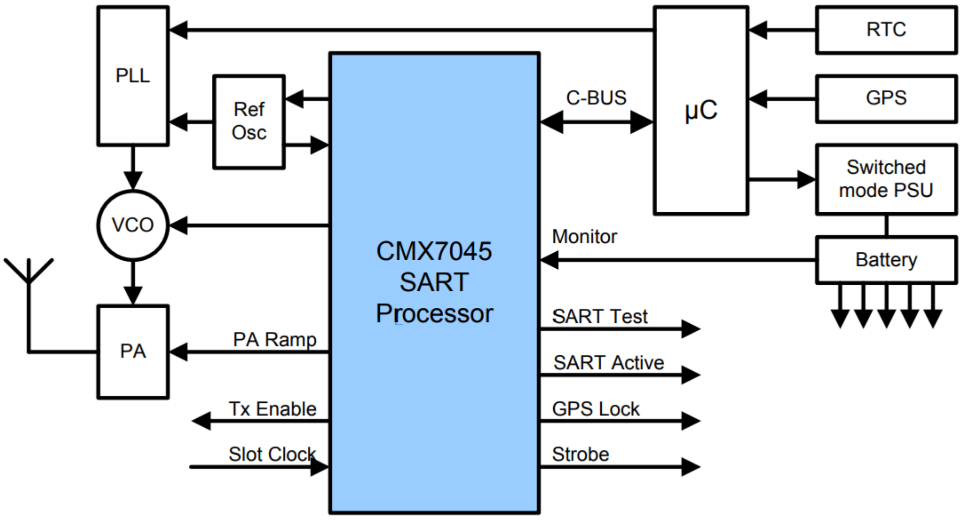


Figure 3.2: CMX7045 proposed system diagram, reproduced with permission from CML [20]

The alternative to using a special purpose AIS device is to use a general purpose transmitter. While many products fall into this category, not many of them are capable of generating signals around 162 MHz. NXP's OL2385 and Silicon Labs' Si446x-series are products that seem like good candidates for this design. These two devices have very similar characteristics, both of them cover the desired frequency band and can achieve relatively high output power (respectively 14dBm and 20dBm). However, the Si446x series seems like the best candidate of the two considering it has a standby current draw of 50nA compared to 700nA for the OL2385. As discussed in Section 2.1.2, the standby current draw could be eliminated by gating the supply voltage to the device, but that is an unnecessary addition of complexity. The Si446x series also seems to be more widely used, which might mean that there is more documentation, example code etc. This could again suggest a shorter design time.

The choice is now narrowed down to either the special purpose AIS MOB processor from CML Microcircuits or the general purpose device from Silicon Labs. This becomes a choice of increasing the hardware complexity and power consumption, for shorter design time and less complexity in the code. The similar system designed by Y. Li et al was based around the CMX7045 [3]. If this system shares the same basic structure, any reduction in size and power consumption will likely have to come from different parts of the system. Taking into consideration that this design needs to have a smaller physical size, and therefore also a lower power consumption than existing designs, the better choice has to be the device from the Si446x series. By selecting a different system structure than that of previous work, the potential for improvements should be greater. Although this change in structure results in more complexity in the firmware design, the design goals of low power consumption and a small size need to take precedence over the design time.

3.2.2 MCU

In contrast to RF-transmitters covering the AIS-frequencies, low power MCUs with state-of-the-art performance are widely available from a large group of manufacturers. This means that the design time and price of the device can be considered more. Since the designed system is likely to stay inactive for several years, one of the most important considerations will be the power consumption the selected MCU can have while waiting to be woken by water detection or a push from a button. The device also needs to have a low power consumption during the waiting periods when activated while keeping track of time.

The trend for most microcontroller manufacturers has been to add more peripheral functionality into the devices such as hardware cryptography accelerators, ADCs and more. This design neither has the need for much computing power, nor many peripherals. However the MCU will have to communicate with other devices, so hardware implementations of common on-board communication protocols would help improve the efficiency and power consumption of the system. Budget MCUs with very little functionality would be a good choice for this system, but as it happens there is one particular device that could help bring both the price and the physical size of the system to a minimum, while still providing state of the art power efficiency. This device is the EZR32HG ("Happy Gecko") from Silicon Labs, which is essentially a system-on-chip containing an ARM-based MCU, and Si4463 transceiver [21]. If the CMX7045 had been selected, the system would require three devices to generate the correct RF signals: An MCU, the CMX7045, and a VCO. By selecting the EZR32HG, all those devices are replaced with one single device. A functional diagram of the EZR32HG is shown in Figure 3.3. This device can achieve a power consumption of 20nA while inactive [22], and the transmitter part of the system has otherwise the same performance as described in the previous section.

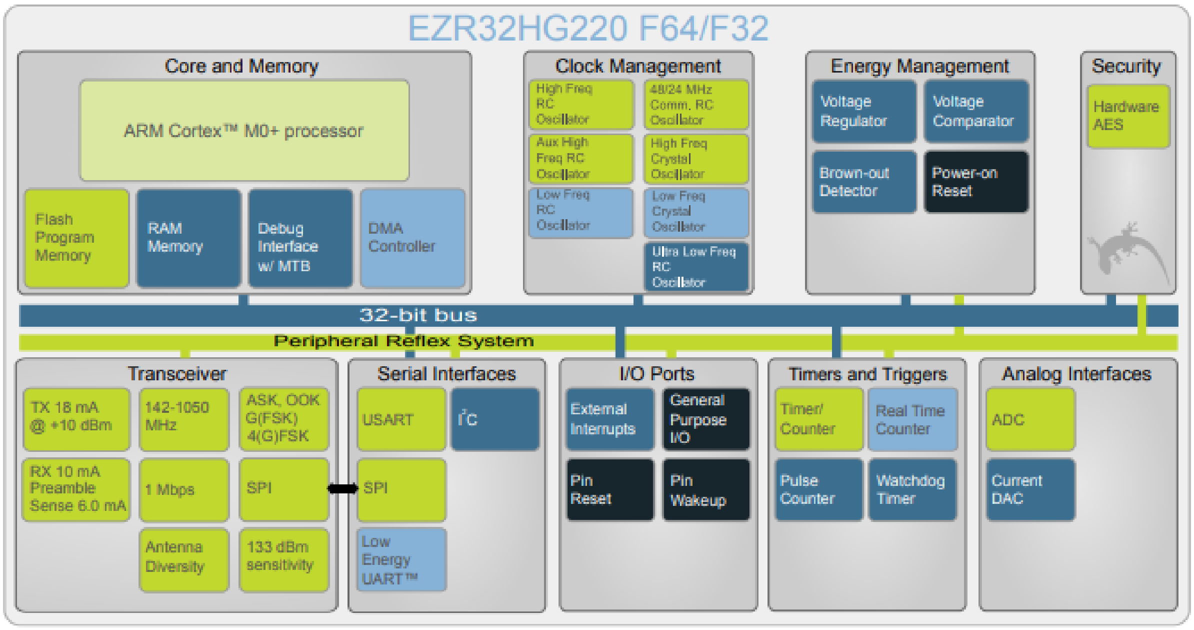


Figure 3.3: EZR32HG functional diagram [22]

3.2.3 Power amplifier

The chosen transmitter has a selectable power output up to 20 dBm, while the finished system should have an output power of 600 mW ± 3 dB. It would be beneficial to be able to compensate for losses in the antenna and the rest of the RF path, so a power amplifier that can achieve at least 1W/30dBm of output power with an input power of 20 dBm or less would be a good start. Since this needs to be a relatively high power amplifier, that will be used in a design where a small physical size is one of the main goals, the heat dissipation becomes very important. First of all the amplifier should be efficient, since that will result in a smaller amount of power needing to be dissipated as heat, and the amplifier should have good thermal characteristics leading to efficient and fast heat dissipation.

From a design-time point of view, it would be ideal to use a "black box" power amplifier that only needs a single voltage supply, RF input and RF output. But as for the transmitter, there are not many products specially made for AIS frequencies. General purpose amplifiers that cover a wide range of frequencies seems to be the only available solution. For such general purpose amplifiers, matching the input and output and supplying both a main supply and a bias voltage is usually necessary. Because of this, it seems that building the amplifier from a transistor results in about the same amount of work as using a complete amplifier.

In the end, using the AFT05MS003N LDMOS transistor from NXP was decided. There are many candidates that could be chosen, and considering every available possibility is not feasible, but this transistor was chosen for some main reasons: The manufacturer supplies an example design covering broadband VHF including the AIS frequencies. The device is well within the requirements listed above. The manufacturer supplies a model that can be used for simulation of the device. The author is not particularly experienced with RF amplifier design, but having the broadband example design as a fallback, and a model of the device for simulation helps with the design process. The supply voltage used in the reference design of the selected transistor is set at 7.5 V. This raises the need for a voltage regulator, and for this, the MIC2288 from Microchip is chosen. This regulator can handle a current of 1 A and has an expected efficiency of around 80 % [12]. To minimise the current draw of the power amplifier when not in use, the input voltage to the regulator will be gated using the low resistance Si2323 transistor [23].

3.2.4 GPS

To reduce the design time, it would be beneficial to use a complete GPS module with an integrated antenna in this design. The ideal device would be able to operate in the same voltage range as the MCU in order to reduce the need for regulators, as well as having an overall low power consumption. Important measures affecting the average power consumption of such devices include the current draw during acquisition, the current draw during backup, as well as the time to first fix (TTFF). The TTFF indicates the time that it takes the module to acquire its position, and this time depends on whether no previous data is available (cold start), or previous data is available (hot start). Such modules include a backup mode, where previously acquired data is stored and an accurate clock is running to keep track of the exact time. This backup data is what enables hot starts. Table 3.1 compares some different candidates for this design.

Table 3.1: comparison of GPS modules

GPS module	Acquisition current draw	Backup current draw	Supply voltage	TTFF Cold start	TTFF Hot start
ublox CAM-M8Q [24]	26 mA	15 µA	2.7-3.6 V	29 s	1 s
ublox CAM-M8C [24]	26 mA	100 µA	1.65-3.6 V	29 s	1 s
Quectel L80 [25]	25 mA	7 µA	3-4.3 V	15 s	1 s

The only device in Table 3.1 that is able to operate in the same voltage range as the MCU, is the CMA-M8C from ublox. This device is also the one with the highest backup current, which is unfortunate for the overall power consumption. Because of this, the Quectel L80 will be chosen for this design, as it has the lowest stated current consumption and acquisition times of the compared devices. This choice does however come at the cost of the need for an additional voltage regulator in the design. The MCP1256 from microchip will be used as the regulator for the GPS module. This is a regulator that switches at a relatively low frequency of 650 kHz, which causes lower noise at the frequencies used by the GPS module. This regulator has an input range of 1.8 V - 3.6 V, and a fixed output voltage at 3.3 V. At an input of 2.8 V and a current draw of 50 mA, the regulator has a power efficiency of 76 % [13]. To minimise the current draw of the GPS module and its power supply, the low resistance Si2323 transistor [23] will be used to gate the input voltage.

3.2.5 Battery

Choosing a battery for this design might not be the most challenging part of the design, but it is a task that should not be taken too lightly. The system should have a long lifetime when inactive, and this imposes requirements on the self-discharge rate of the battery. In addition, one could argue that this limits the voltage range of the selected battery. If the battery has an output voltage that cannot be directly utilized by the MCU, a voltage regulator has to be used. This does not only add an additional component but also increases the power consumption of the device, which becomes especially important when the system is inactive and needs to have a very low power consumption. Furthermore, the system will have an irregular power consumption with large spikes in the current draw when AIS messages are sent. Batteries have a limit to the current that can be drawn from them, and while this can be battled by adding capacitors, the spikes, in this case, would result in very large capacitors. It would be beneficial if the selected battery type is widely commercially available. Finally, an obvious requirement is that the physical size of the battery should be kept small, while the capacity should be large enough to power the system for the required amount of time.

Using rechargeable battery technology like Lithium-ion or Lithium-polymer can quickly be ruled out since these batteries typically have quite high self-discharge rates [26] and voltages well above what can be used by the selected MCU [27]. In addition, this is not a system that should require any maintenance (i.e charging). Non-rechargeable lithium-based batteries come in a number of shapes and sizes and have a relatively high energy density as well as a voltage output that can be directly used by the MCU. Some of the most common sizes are button-cell batteries, which certainly have a small size. These button-cell batteries would have a quite low capacity for this design, as well as not being able to supply sufficient current when the system is transmitting. A more fitting size is the CR123 type lithium manganese dioxide battery. This type of battery is often used in cameras because they can provide the high output current needed for the camera flash. Typical capacity values for this type of batteries is around 1500 mA h, when discharged down to 2 V [5]. The specific battery that will be used is a CR123 battery from Energizer. An example of a discharge curve of this battery is shown in Figure 3.4. From this figure, it can be seen that the output voltage varies throughout the discharge curve. The rest of the system is designed to operate down to a voltage of 1.8 V, and the system should, therefore, be able to utilise most of the energy from this battery.

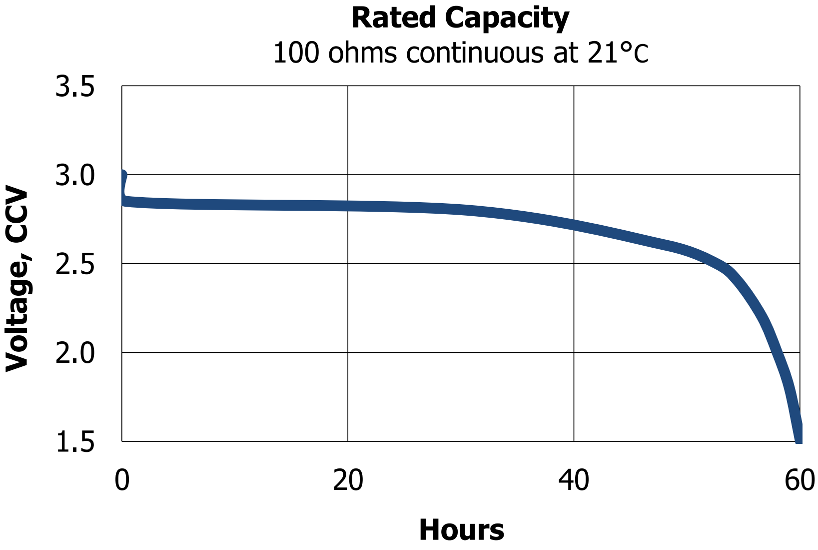


Figure 3.4: Energizer 123 discharge curve [5]

3.3 Power consumption estimate

After selecting individual components, the power consumption of the system can be estimated. Although the components have been chosen with low power consumption in mind, it is important to estimate the consumption of the final system. If the estimated power consumption of the device is too high, there is no point in going further with the selected high-level design. While power consumption is the measure of interest, it is often helpful to think about the current draw instead. This is because the manufacturers of both batteries and silicon devices usually describe capacity and consumption in terms of current. The power consumption can be divided into two modes of operation: Inactive mode for when the device is inactive and waiting for inputs, and active mode for when the device has been activated and is sending distress messages. When estimating the power consumption, 2.8 V can be used as an average for the battery voltage. This value seems to fit with the discharge curve in Figure 3.4.

3.3.1 Inactive mode

In inactive mode, the only part of the system which is powered is the MCU, which can have a current draw of 20 nA while still being able to respond to external pin changes like a test button or water detection [22]. If the only current draw during inactive mode came from the MCU, this would mean that a battery with a capacity of 1500 mA h could sustain the device in inactive mode for over eight thousand years. This is far from a serious estimate, but it shows that the consumption from the MCU itself can be neglected in inactive mode. There will be several other contributors to the current in inactive mode, like capacitor leakage from decoupling capacitors, but these are even smaller than the contribution from the MCU. Since these currents are so small, the limiting factor becomes the shelf life of the battery itself, which is due to self-discharge of the battery. CR123 batteries have a typical shelf life of 10 years, meaning that they will still hold most of their capacity up to that point [28].

3.3.2 Active mode

In active mode, there are a lot more contributing factors to the current draw. In this mode of operation, the MCU, GPS, transmitter, and PA are all active. To estimate the total current draw, the current draw of each module while active can be multiplied with the expected time that each module is active.

The current draw of the GPS module can be estimated by using the values of discussed when the module was chosen. In Section 2.3.4.1, it was discussed that the GPS should update the position every minute. The consumption of the first acquisition can be neglected in this estimate as it has will quickly become much smaller than the consumption of the subsequent acquisitions. The acquisition current is 25 mA, the backup current is 7μA, the expected TTFF is 1 s, and the regulator efficiency is 76%. The GPS module is operated at 3.3 V, and 2.8 V can be used as an average voltage for the battery. From this, the average current draw can be calculated as follows.

$$I_{GPSavg} = \frac{25\text{mA} \cdot 1\text{s} \cdot \frac{3.3\text{V}}{2.8\text{V} \cdot 76\%}}{60\text{s}} + 7\mu\text{A} = 0.65\text{mA}$$

The manufacturer of the transmitter states a 69 mA power consumption at +20 dBm output power and 169 MHz [22]. The device will be operated at both a lower output power, and a lower frequency, but this value should be good for use in this estimate. In Section 2.3.4.1, it was discussed that the system will send a burst of eight messages every minute, and the individual messages will last for 26.7 ms each. From this, the average current draw of the transmitter can be estimated as follows:

$$I_{TXavg} = \frac{8 \cdot 26.7\text{ms} \cdot 69\text{mA}}{60\text{s}} = 0.25\text{mA}$$

The power amplifier will be active at the same time as the transmitter, but it will likely need be activated a short time before the transmitter to ensure that the whole signal is amplified. For this reason a time of 30 ms is used instead of 26.7 ms in this estimate. The consumption of the power amplifier can be calculated by using the required output power, and estimates for the efficiency. Earlier it was discussed that the voltage regulator supplying the voltage for the PA has an efficiency around 80 %. If a relatively conservative efficiency of 60% is used for the PA, the average current draw from the PA can then be estimated to be

$$I_{PAavg} = \frac{8 \cdot 30\text{ms} \cdot \frac{1\text{W}}{2.8\text{V}} \cdot \frac{1}{60\% \cdot 80\%}}{60\text{s}} = 3.0\text{mA}$$

The MCU has a current draw of about 2 µA while inactive, yet being able to wake up after a set time by using its internal low-frequency timer [22]. The MCU will have to be active when the GPS module is active in order to check incoming GPS data, as well as controlling the PA. When active, the MCU draws about 1 mA [22]. If an estimate of two seconds of activity per minute is used, the current draw of the MCU can be estimated to be

$$I_{MCUavg} = \frac{2\text{s} \cdot 1\text{mA}}{60\text{s}} + 2\mu\text{A} = 0.04\text{mA}$$

In summary, the different estimates can be added together to give an estimate of the total current draw of

$$I_{avg} = 0.65\text{mA} + 0.25\text{mA} + 3.0\text{mA} + 0.04\text{mA} = 3.94\text{mA}$$

In the work of Y. Li et al [3], a similar system was designed, and the achieved average current draw in active mode was 66.6 mA at a voltage of 6 V. In that work, the designed system was compared to commercially available products and found to have a lower power consumption. This means that this work show promise in greatly reducing the power consumption of such devices if the estimated values can be achieved.

3.3.3 A note on indicator consumption

The prototype design does not include an indicator, although AIS MOB devices that wish to comply with applicable standard needs a way of indicating the device state. The existing devices mentioned in Section 1.3, include light emitting diodes (LEDs) as their indicators. It is, therefore, necessary to estimate the added power consumption from an LED indicator in order to be able to perform meaningful comparisons.

In order to make this estimate, the power consumption of the 0.5 W LM281+ LED series from Samsung is used [29]. This type of LED is intended for use as the flash in camera phones, and should, therefore, represent a relatively high-intensity light. A high-intensity light is chosen for the estimate since it would aid in finding personnel in the water. The LED could be used to flash at different intervals to indicate different states of the system. Experimentally, it was found that flashes with a duration of 5 ms is easily visible mid-day outdoor light conditions. If the LED is flashed at a rate of once every second, this would lead to an average current draw of

$$I_{LEDavg} = \frac{\frac{0.5\text{W}}{2.8\text{V}} \cdot 5\text{ms}}{2\text{s}} = 0.45\text{mA}$$

Since the devices discussed in Section 1.3 has no mention of the flash durations used, the estimated value is questionable when it comes to comparison of the power consumption.

However, the applicable standards mention no requirements when it comes to flash duration. The estimated value should, therefore, represent the consumption of highly visible indicator.

3.4 Antenna

3.4.1 Possible antenna solutions

The antenna solution for this system quickly becomes a very challenging design and time-consuming process. This work focuses on making a functioning prototype, and for this reason, no particular antenna will be chosen or designed. Instead, the output power will be measured using a spectrum analyser, and when the system is to be tested with other AIS equipment, an arbitrary antenna (or none at all) can be used.

Existing AIS MOB devices use different forms of retractable antennas that are deployed upon activation, two such solutions are shown in Figure 3.5. The same type of solution could be used for a device that is fully integrated into a life jacket, as the retractable antenna part of the system could be fastened on the outside of the life jacket.

If the MOB device and the life jacket are manufactured as one unit, placing the antenna on the inside of the life jacket could be an interesting approach. Figure 3.6 shows how an antenna could be placed on the inside of a life jacket. This could be accomplished with a flexible metal foil/tape, and it has some possible benefits over the retractable solutions: An integrated antenna would have no need for an automatic deployment system, it would automatically be placed away from the user when the life jacket inflates, and the life jacket keeps it over water.

Figure 3.5: Existing MOB antenna solutions [2] [30]

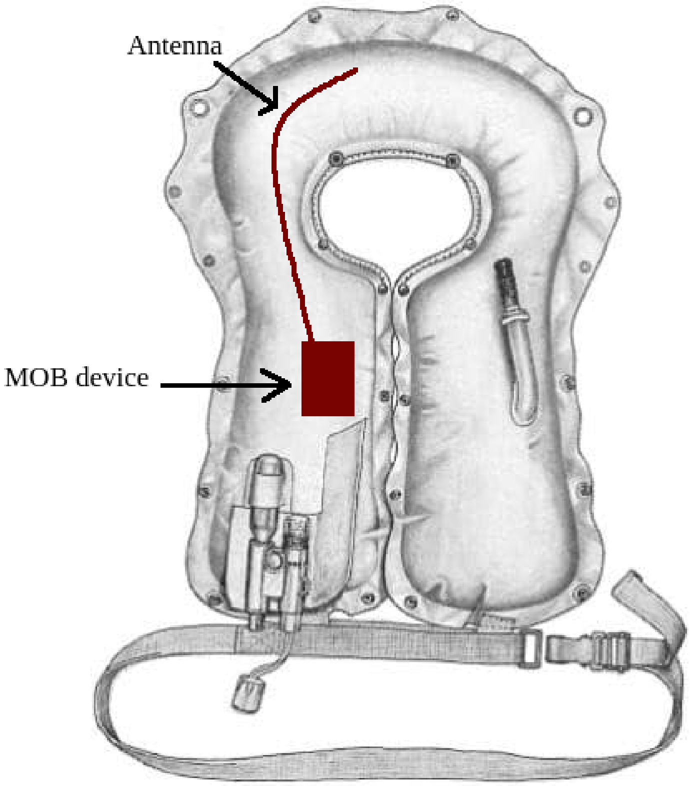


Figure 3.6: Integrated antenna solution, adapted from [31]

3.4.2 Range estimates

There are several ways of estimating the range of the solution. One way would be to use a suitable propagation model and use typical values for AIS receiver sensitivities, antenna gains etc. Using such a model would quickly become quite uncertain, as any chosen model would necessarily be just an estimate, and there are many unknown parameters.

Instead of depending on a propagation model, the range of the solution will be estimated by using the range of existing solutions. There are two main range affecting parameters that can be controlled by the designers of MOB devices. Those are the antenna performance, and the transmit power. The transmit power can be measured, but since no antenna will be designed in this work, one can instead assume that performance similar to existing solutions should be achievable. Table 3.2 shows the range and transmit power of existing solutions. The manufacturers differ in whether the values are given in minimum, typical or maximum range, and on whether the transmit power is compensated for antenna efficiency or not.

Table 3.2: Range and transmit power of existing solutions

Device	**Range**	**Transmit power**
Y. Li et al [3]	5 nmi (minimum)	28 dBm ± 2 dB
Ocean signal MOB1 [6]	5 nmi (maximum)	30 dBm
Kannad R10 [7]	3.5 nmi (typical)	33 dBm
Simy-beacons My-AIS [32]	5-10 nmi	30 dBm (ERP)

The two antenna solutions shown in 3.5, are the ones used by the MOB1 and the MY-AIS. If a similar antenna solution is used with the system designed in this work, the expected range would be in the 5 nmi range. For a fully integrated solution, it is not wise to make assumptions on the range without having tested such a solution.

Chapter 4

Implementation

4.1 GPS hardware

As discussed when the GPS module was selected, it requires a voltage regulator in order to be used with the battery solution selected. Since the designed system could stay inactive for several years, it is desired to minimize the inactive power consumption. The selected MCP1256 regulator has a quiescent current of 0.25 µA, which is an order of magnitude larger than that of the MCU [13] [22]. In order to battle this, the Si2323 low resistance p-type MOSFET from Vishay used to gate the input voltage of the regulator [23]. The backup circuitry of the GPS module has a separate supply, which can operate at voltages down to 1.5 V [25]. Since the backup current is low, this means that the backup supply voltage can be supplied (and controlled) directly from a General Purpose Input Output (GPIO) pin of the MCU. Figure 4.1 shows a simplified schematic of the GPS supply circuitry.

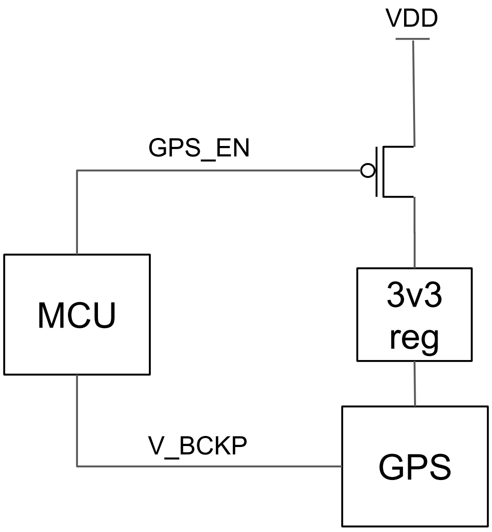


Figure 4.1: Simplified GPS supply schematic

4.2 Water detection and test button

In order to activate the device, either for test purposes or water detection, it is desirable to do so by changing the value of a GPIO pin of the EZR32. The EZR32 is capable of waking up from a very low power consumption mode referred to as Energy Mode 4 (EM4) by the manufacturer, by detecting pin changes.

For the test button, this is straight forward. A simple push button, with a so-called debounce low-pass filter, would achieve this. For water detection, the conductivity of the water could be exploited to achieve a similar effect. The EZR32 has internal pull resistors with values of 40 kΩ [22]. By using the conductivity of water as a second resistor, a voltage divider can be constructed. This equivalent circuit of this concept is illustrated in Figure 4.2. The EZR32 considers inputs lower than $0.3 \cdot V_{DD}$ as logical low [22], so by starting with the equation for voltage dividers, it can be shown that a water resistance of less than 17 kΩ will cause the water detection input to be pulled low. While the conductivity of water varies depending on the ion concentration, typical values for seawater are around 50 Ω^{-1}/m [33], which would result in an equivalent resistance for the water of 0.5 Ω if the distance between the voltage source and the water detection pin is 1 cm. This should result in a simple and effective way of detecting water, and the same effect could be achieved with an external pull resistor if different sensitivities are required.

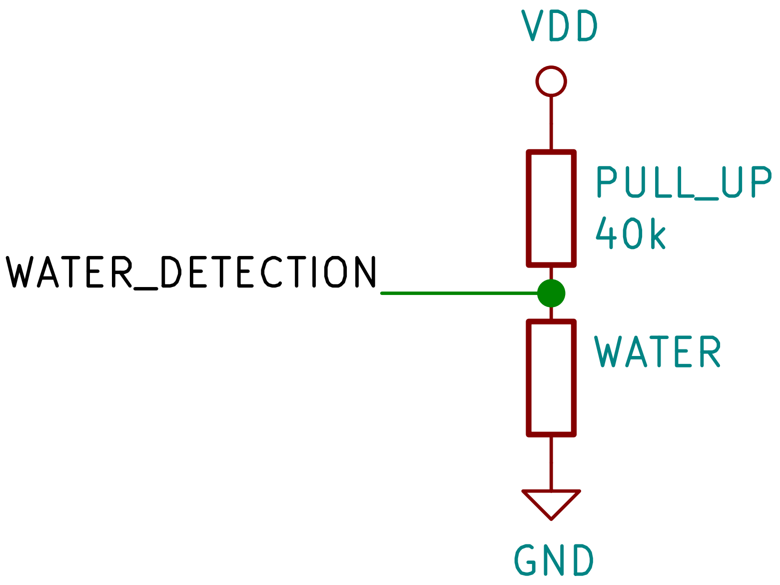


Figure 4.2: Water detection equivalent circuit

This concept for water detection has the advantage of taking very little space, while still allowing the rest of the system to stay at in a low energy mode. A disadvantage is that this concept could be prone to unwanted activations from water splash or rain. Compensation for this can be made in the firmware design, by confirming that water is detected over a longer period of time after the system has been woken up.

4.3 RF path

The RF path in this design involves the transmitter, power amplifier and antenna port. The design will be based on a standard 50 Ω impedance, so all blocks in the RF path will be matched to this value. While a finished product should have the PA on the same circuit board as the rest of the circuit, this work uses a separate board to simplify the matching procedure. 50 Ω coaxial connectors are used on both boards for the interconnection.

4.3.1 Transmitter output network

The SI4463 transmitter has an internal class-E amplifier with an adjustable output power of up to 20 dBm [22]. The output of class E amplifiers is essentially a square wave, so strong harmonics will be present. To battle this, a harmonic termination circuit and a low pass filter are combined. The idea behind this is to terminate the harmonics in the termination circuit while letting the fundamental frequency pass through the low pass filter. The output network of the transmitter will be based on a reference design from Silicon Labs [34] and adapted to the frequencies used in this design.

The harmonic termination circuit consists of a capacitor and an inductor in parallel, with a 50 Ω resistor in series for termination. The parallel LC-circuit has an impedance peak at its resonance frequency, f_0, given by equation 4.3.1 while having low impedance at other frequencies. By selecting component values such that the circuit resonates at the fundamental operating frequency, the harmonics will pass the LC circuit and get terminated while the fundamental frequency will not pass.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{4.3.1}$$

In order to guide the fundamental frequency through to the next stage, while blocking the higher frequency harmonics, a Chebyshev low pass filter is used. This filter is designed such that the cut-off frequency is a bit over the fundamental frequency. The low-pass filter is designed using a Chebyshev filter design tool, and the harmonic termination circuit is designed using equation 4.3.1. The remaining component values follow the recommendations of the manufacturer [34]. The schematic of this part of the RF circuit can be seen in Figure 4.3.

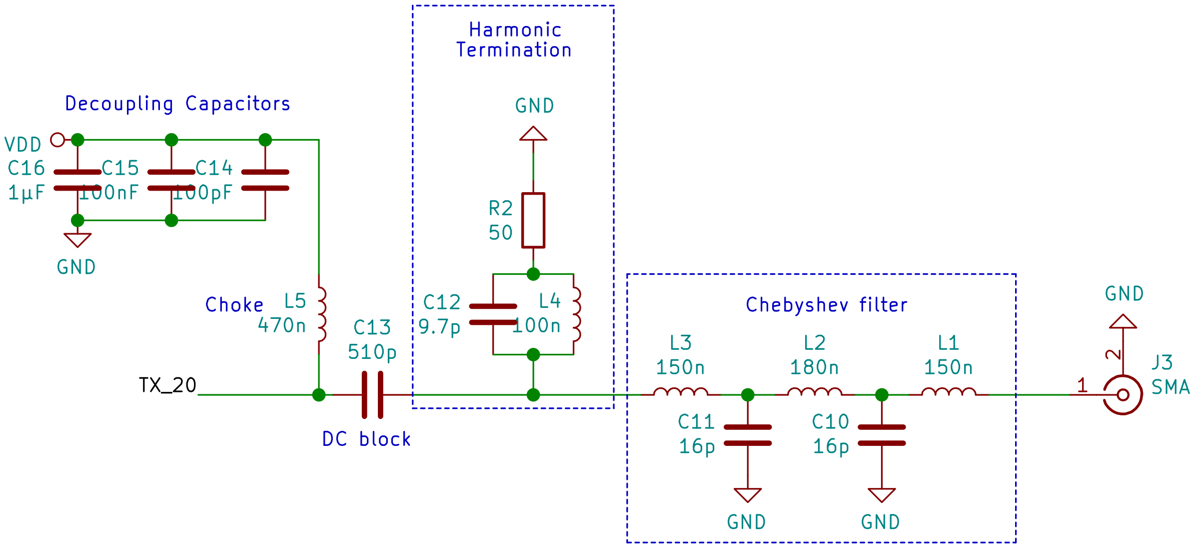


Figure 4.3: Schematic of output from transmitter

The frequency response of the output network can be seen in Figure 4.4. This frequency response is obtained through simulation. From the frequency response, it can be seen that the fundamental frequencies around 162 MHz will pass, while the first harmonic at 324 MHz will be attenuated by around 50 dB. Higher harmonics will naturally be attenuated further.

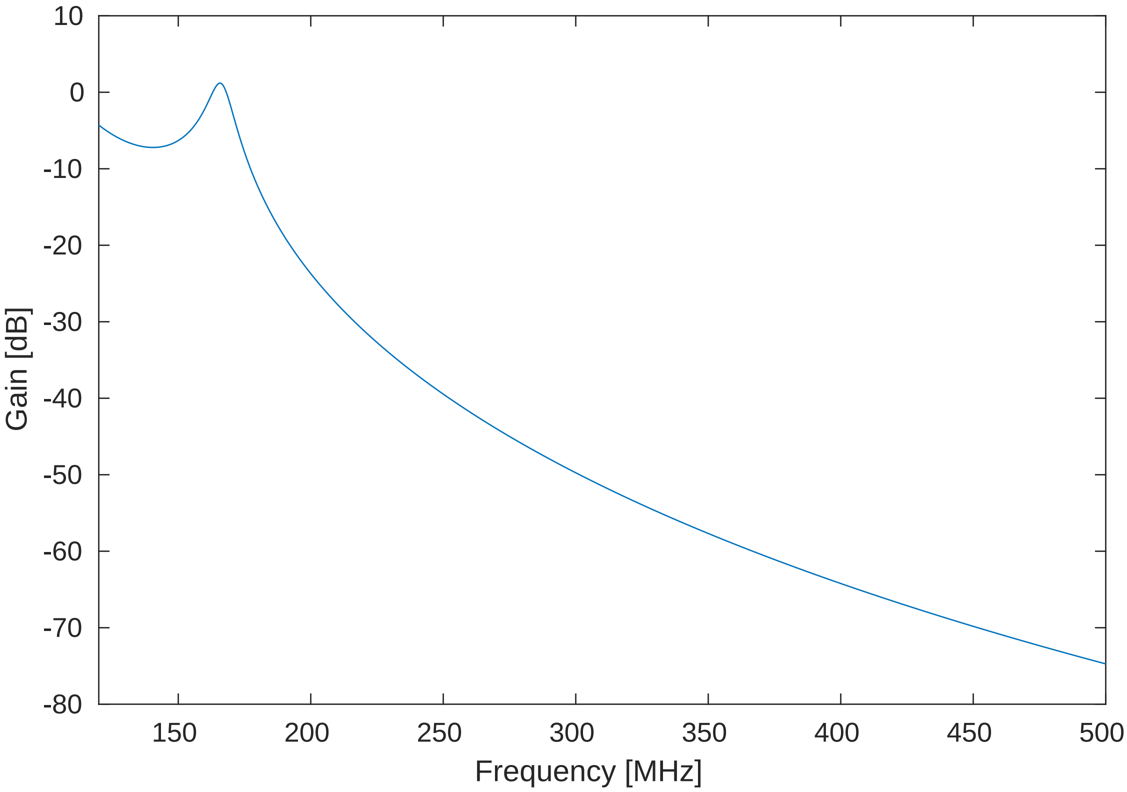


Figure 4.4: Frequency response of transmitter output network

4.3.2 Power amplifier

In order to achieve the desired voltages for bias and drain voltage of the amplifier, the MIC2288 regulator is used [12]. This power supply circuit is designed based on the recommended circuit from the manufacturer, such that the regulator outputs 7.5 V. To get the bias voltage, a voltage divider is used. The power amplifier design will be loosely based on a reference design from the manufacturer [35]. The reference design is a broadband amplifier for the range 136-174 MHz and will be adapted by changing the input and output networks for a simpler matching network. No output filter will be designed, which might lead to harmonic distortion of the signal. As stated the main goal of the amplifier is to provide the desired output power, so that accurate comparisons of the power consumption can be made with existing solutions. Figure 4.5 shows the design, without specified values for the matching network. Through simulations, it is found that an 18 Ω resistor on the gate of the transistor is required to make the amplifier stable.

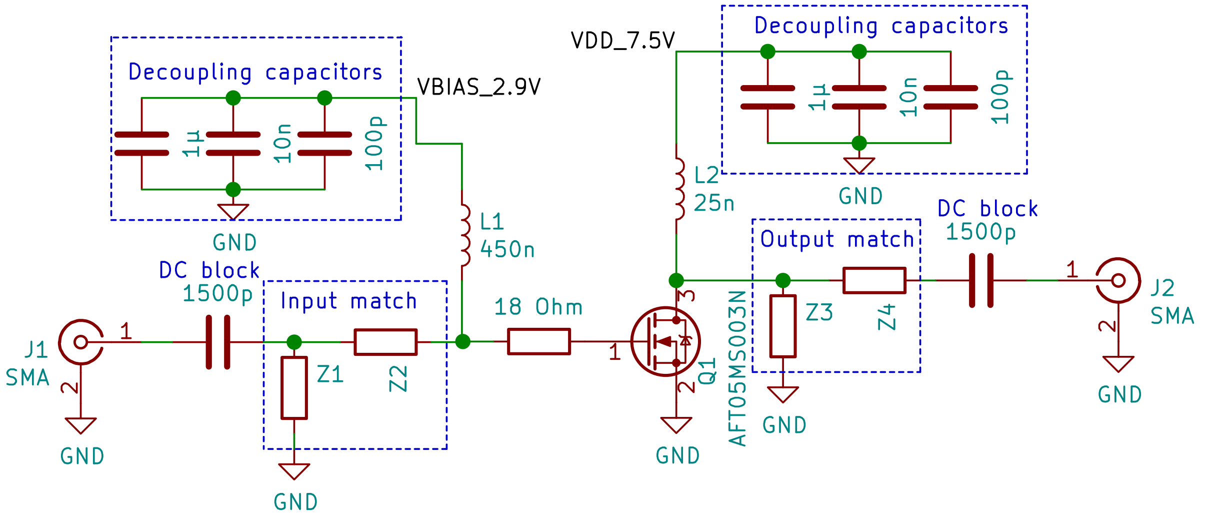


Figure 4.5: Amplifier schematic

In order to match the input and output of the amplifier to 50 Ω, a measurement of the scattering parameters (S-parameters) is taken without any matching components. Figure 4.6 shows S_{11} and S_{22} of the unmatched circuit. In this figure the values are normalised, meaning that the centre value of $1.0 + 0j$ represents 50 Ω. The required values for the matching components is obtained using a smith chart, these values are listed in Table 4.1. Figure 4.7 shows S_{11} and S_{22} after matching, where the values are considerably closer to 50 Ω. Figure 4.8 shows S_{12} and S_{21}, where S_{21} represents the gain of the amplifier. The gain is found to be around 20 dB at 162 MHz.

Table 4.1: Values of matching components obtained by smith chart

Component	Type	Value
Z1	Capacitor	27 pF
Z2	Inductor	24 nH
Z3	Capacitor	9 pF
Z4	Inductor	37 nH

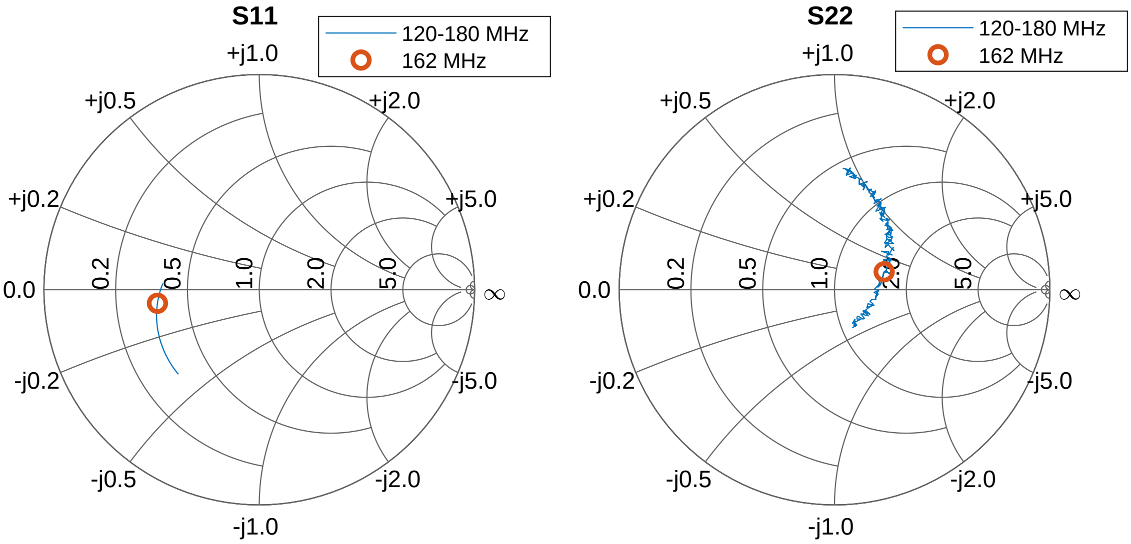


Figure 4.6: S_{11} and S_{22} of amplifier before matching

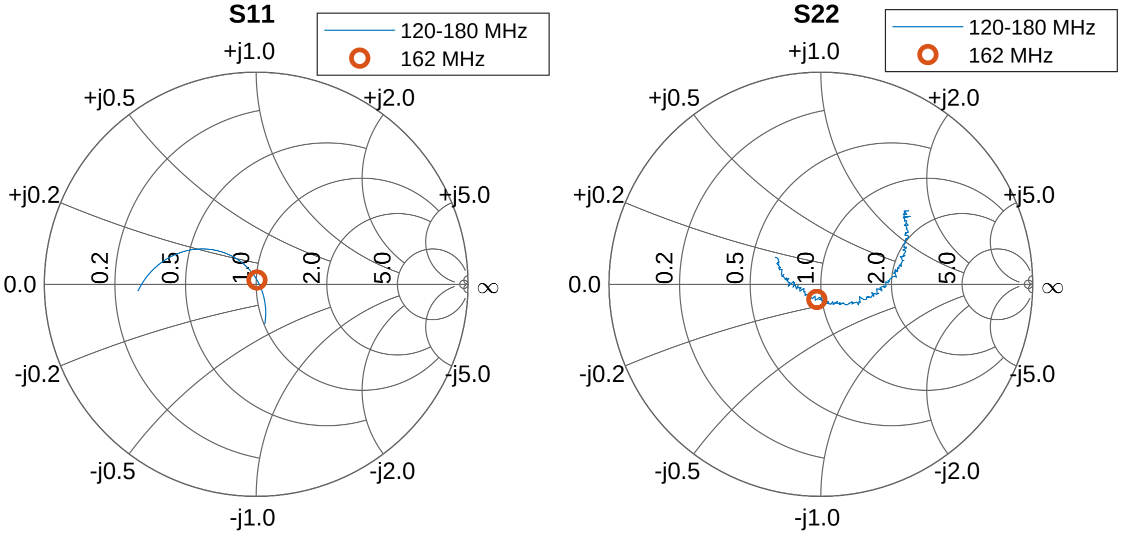


Figure 4.7: S_{11} and S_{22} of amplifier after matching

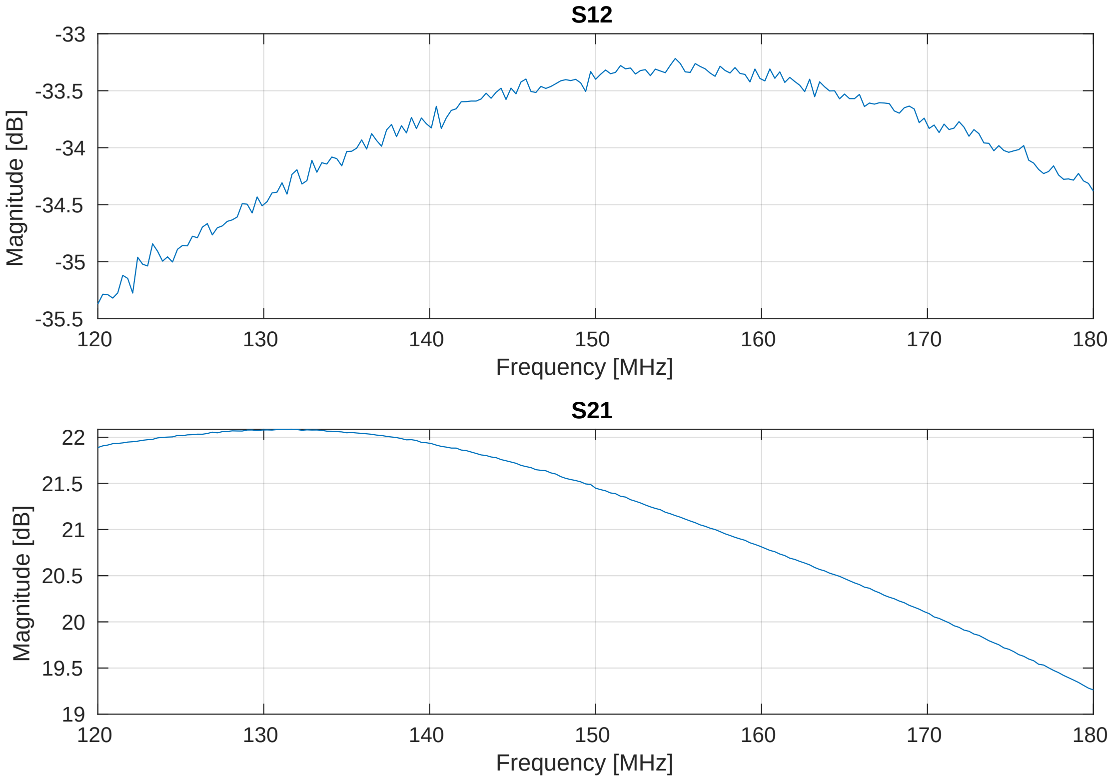


Figure 4.8: S_{12} and S_{21} of amplifier after matching

4.4 Firmware

During the component selection process, it was decided to use general hardware as opposed to hardware specifically meant for AIS applications. This increases the complexity of the firmware design, as it needs to handle AIS message generation, AIS timing requirements, and the exact configuration of the radio transmitter. All the firmware in this work will be written for the EZR32HG MCU, in the C programming language.

4.4.1 Overall system control

Silicon Labs' 32-bit MCUs have an abstraction layer for reducing power consumption referred to as energy modes 0 to 4 (EM0-EM4). EM0 represents normal operation with the highest power consumption. EM4 represents a shutoff mode where all clock sources and RAM blocks are disabled to save power. In EM4 the device can still wake up from external interrupts. When writing the firmware for this work, a combination of staying in the lowest possible energy mode, and cutting power to all inactive parts of the system will be used to achieve low power consumption. Figure 3.1 shows a high-level state diagram for the firmware. This state diagram describes the main states, actions performed immediately upon entering the states, and the events causing state changes. The state diagram also shows how the system will enable and disable modules as they are needed. One thing to note from the state diagram is that the system enters a sleep mode (EM2) when waiting to send the next message. In this mode, the MCU will keep track of time with a low-frequency timer, and the only other active part of the system will be the backup power of the GPS module.

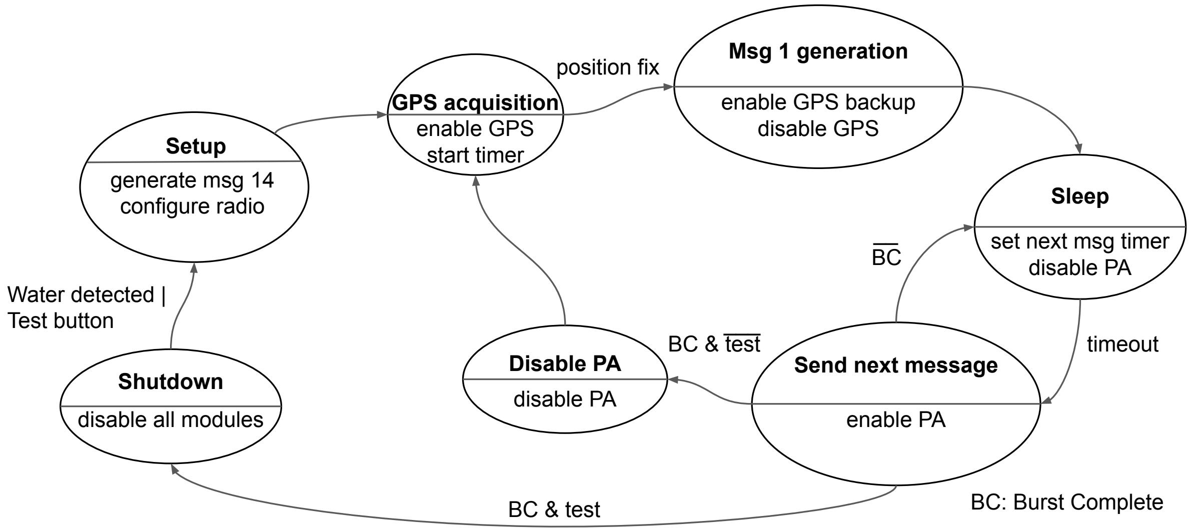


Figure 4.9: System state diagram

Since this is a prototype, some liberties are taken in the firmware design with respect to the AIS MOB specification. One such liberty is that the device is not synced to the start of an AIS frame. This should be done by using the time acquired with the GPS, but the fact that GPS does not account for leap seconds [18] complicates this a bit. Another liberty taken is that edge cases, such as if the system does not acquire its position within one minute is not handled. In this case, the device should transmit a default position. These shortcuts in the firmware design should not affect the overall power consumption in any noticeable way.

4.4.2 AIS message generation

Before AIS messages can be sent, they need to be constructed so that they comply with the protocol. Figure 2.5 in Section 2.3.2 shows the different fields in an AIS message. The generation of AIS messages can be divided into several different tasks as shown in Figure 4.10. In the firmware, the code generation is realised by starting with an empty array of 32 eight bit integers, which is step-by-step filled with the correct content. The actual lengths of the messages used in this work can be lower than 256 bits, so the overall length is kept track of in order to ensure that the transmitter does not keep transmitting for longer than it needs.

The first step in this process is to construct the data field of the message. This field depends on the message type (1 or 14), whether the device is under test or not, and position data including timing and speed over ground. The details of the data field content are described in appendix A.2 and A.1. By realizing that message type 14 does not depend on position data, but only whether the device is under test or not, some computation time can be saved by only generating this message once when the device is activated. Message type 1 will be calculated once each minute if new position data is available according to the AIS requirements [18].

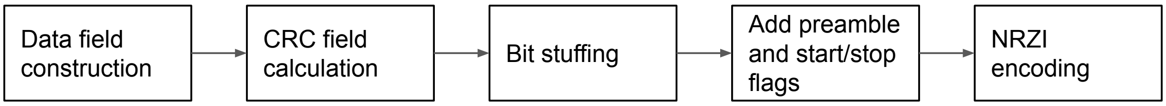


Figure 4.10: Code blocks for message generation

4.4.3 Radio configuration

The SI4463 radio transmitter that resides within the EZR32 device, is as mentioned a general radio transmitter capable of transmitting with several types of modulation and at a wide range of frequencies. In order to configure the radio correctly for this application, a large set of configuration registers can be used. To help with generating the correct values for all the configuration registers, Silicon Labs provides the Wireless Development Suite (WDS) software. WDS helps setting most of the required parameters such as frequency deviation, base frequency and data rate. Table 4.2 sums up the most important configuration options that needs to be set. 2GFSK modulation refers to a binary FSK with a Gaussian filter, and as discussed in Section 2.2.1, the GMSK modulation required for this work is a special case of that. In WDS, the base frequency is selected to be the carrier of AIS channel 1, and since the channel spacing is 25 kHz, AIS channel 2 can be selected by instructing the radio to send on channel 2 (0 would be AIS channel 1). All the parameters in Table 4.2, except the BT product can be entered directly into WDS.

Table 4.2: Radio configuration options

Parameter	**Value**
Base frequency	161.975 MHz
Modulation type	2GFSK
Data rate	9600 Hz
Frequency deviation	2400 Hz
Channel spacing	25 kHz
Gaussian filter BT product	0.4

WDS does not expose any settings to set a pre-modulation filter. Instead, the settings for this needs to be generated manually. The SI4463 transmitter contains registers for setting a 17-tap Finite Impulse Response (FIR) filter for filtering of the pre-modulation signal. This is what will be used to achieve the correct Gaussian filtering. When calculating the values of the FIR filter coefficients, care must be taken since the radio transmitter performs internal oversampling of the pre-modulation signal [22]. The oversampling factor impacts the BT product since the symbol time is altered. The default oversampling factor of the chip is 10 times, so the desired BT product needs to be divided by 10 before calculating FIR filter coefficients. With this in mind, a 17-tap Gaussian FIR filter is derived from the impulse response in equation 2.2.2. Normally, the coefficients of FIR filters are normalized so that they sum up to 1. This can obviously not be entered directly into the Si4463 registers, as they are eight-bit registers. Instead, the calculated values need to be scaled and rounded into integers. The SI4463 lacks documentation on the scaling of FIR filters, but from a set of default filters [36] it can be deduced that the filter should be scaled so that the filter coefficients sum up to a value of 678. The resulting FIR coefficients are shown in Figure 4.11.

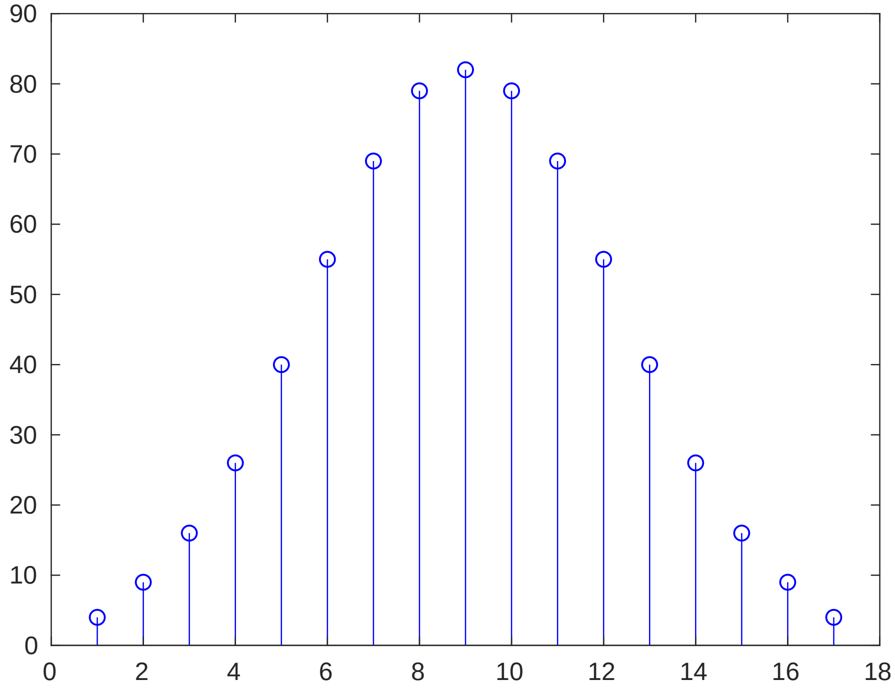


Figure 4.11: Gaussian FIR filter coefficients, BT=0.4

4.5 Circuit boards

Two circuit boards are designed to serve as the finished prototype. Both circuit boards are two layer boards, made with 1.6mm FR4 substrate and with 0.0347 mm ("1 oz") thick copper. The main circuit board contains all the sub-modules except the power amplifier which is on a separate board to simplify the matching procedure. Although the main circuit board is made quite small, there is enough space to add the PA on the same circuit board. The size of the main circuit board is 19x26x67 mm, where each dimension is measured between the two points furthest away. The main circuit board is shown in Figure 4.12. As can be seen in the lower half of Figure 4.12, the battery contributes to a large amount of the total size. The PA circuit board is shown in Figure 4.13, here the board is under test.

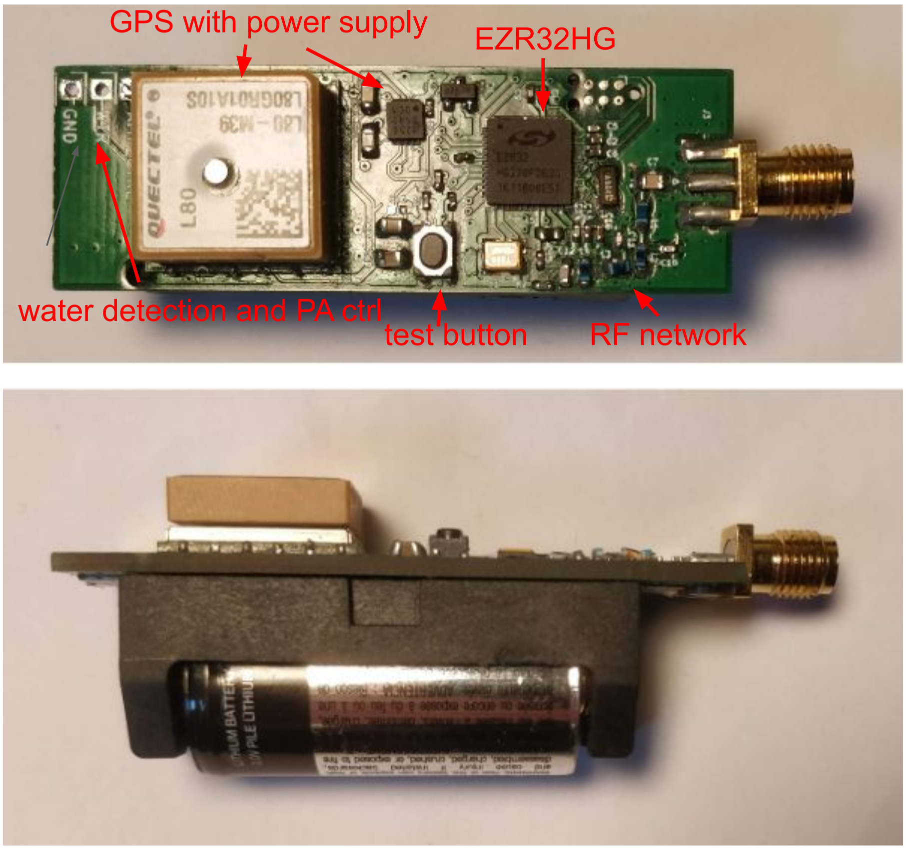


Figure 4.12: Main AIS MOB circuit board

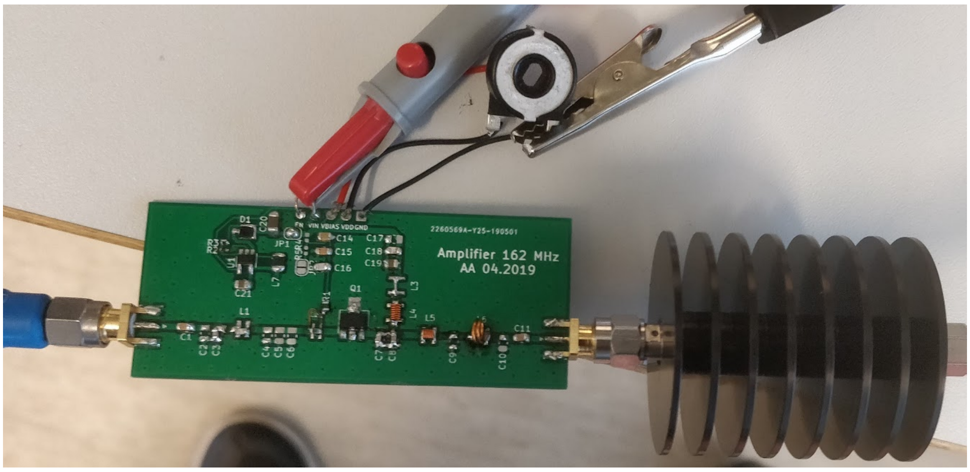


Figure 4.13: PA circuit board under test

Chapter 5

Results

Measurements are taken in order to characterise the system based on its power consumption and output spectrum. In addition, tests will be performed to show that the system sends correct AIS messages, that can be received by standard AIS equipment.

5.1 Transmission and reception of AIS messages

In order to activate the system, the water detection pin is lowered into a bowl of salt water. This caused the system to activate, and start sending AIS messages. To capture these messages, a software defined radio (SDR) from NOOELEC is used [37]. Figure 5.1 shows a spectrogram of an AIS message sent by the system. Here it can be seen that the frequency deviation and the data rate of the signal are as expected. This data can also be compared to the signal broadcasted by a ship shown in Figure 2.4 and the two signals closely resemble each other. As for the message sent by the ship, the preamble, start and stop flag of the message can be identified.

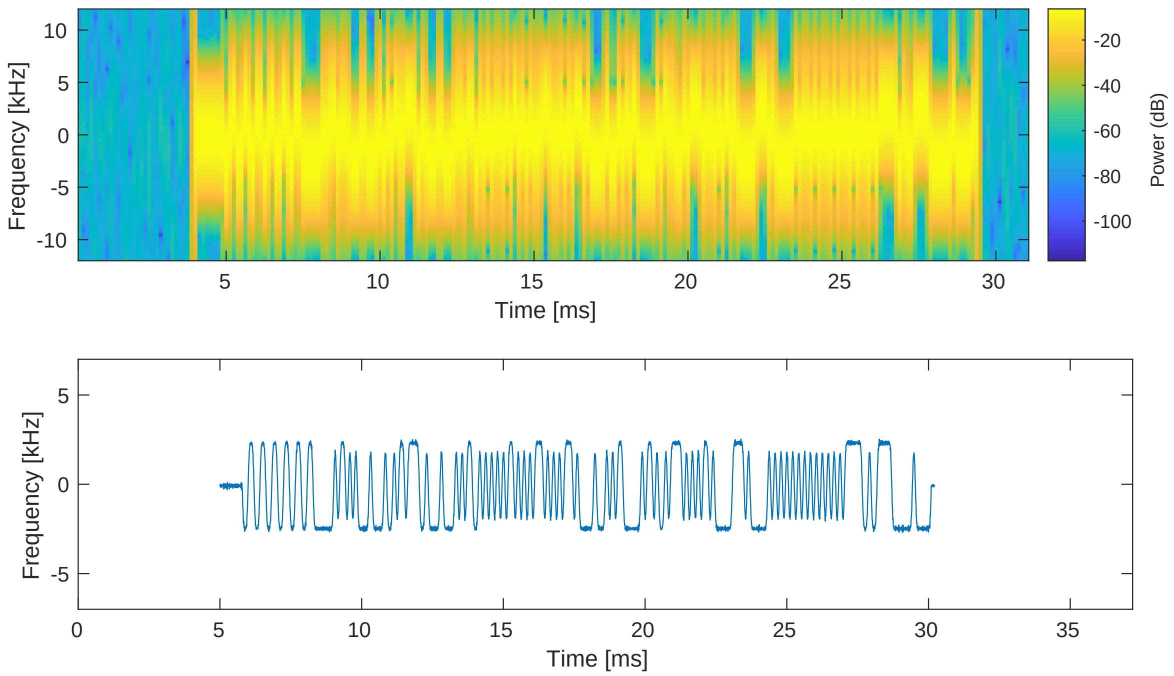
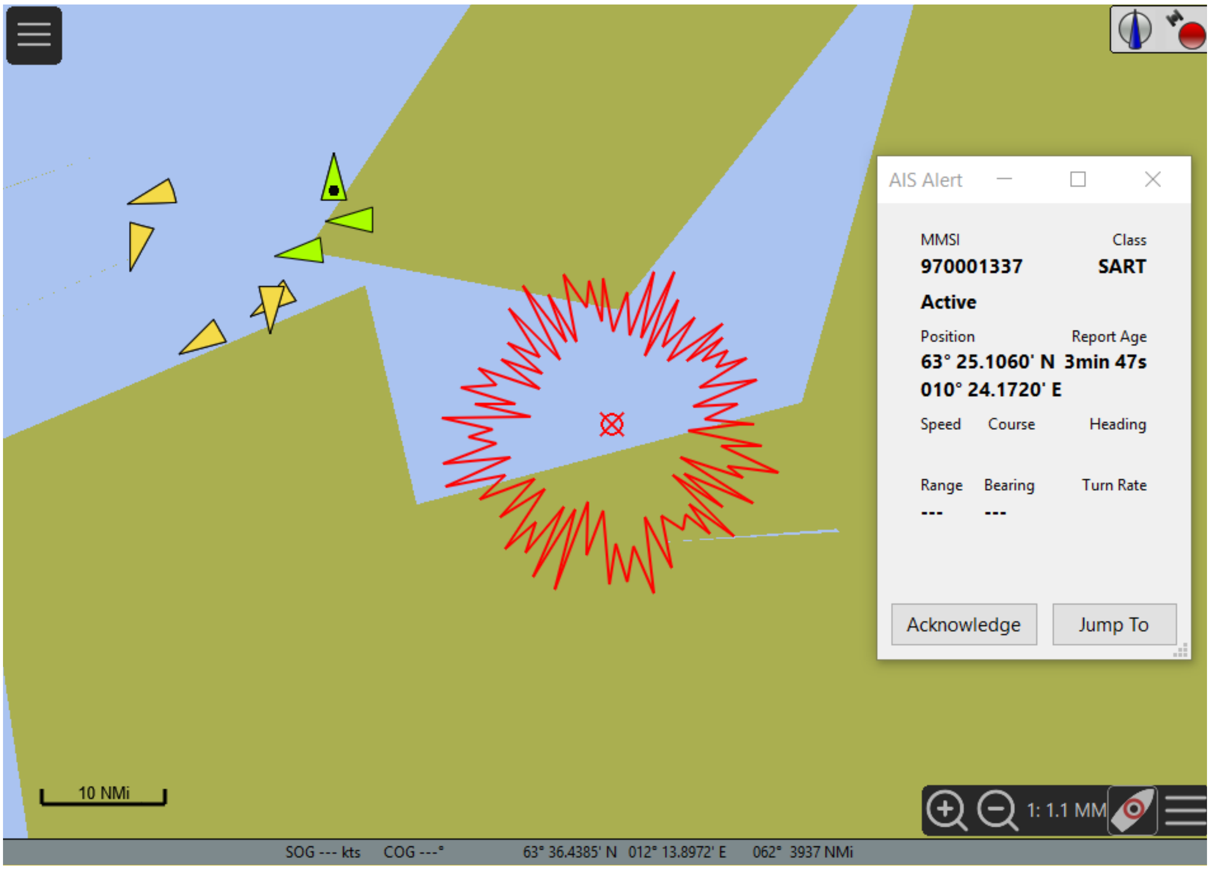


Figure 5.1: Spectrogram of message sent by the system

Although the data from Figure 5.1 could be used to verify if the transmitted data is correct, a simpler and better way is to use an AIS receiver. The dAISy AIS receiver [38] is used together with the OpenCPN chart plotter software in order to receive messages from the system. Figure 5.2 shows the resulting warning displayed in the chart plotter. This test was performed on land, and the reason that the chart plotter displays the warning signal in water is due to the poor resolution of the chart. The sent position was confirmed to be correct within a 10 metre distance.



AIS Alert

MMSI: 970001337

Class: SART

Active

Position: 63° 25.1060' N 010° 24.1720' E

Report Age: 3min 47s

Speed

Course

Heading

Range: ---

Bearing: ---

Turn Rate

Figure 5.2: Reception of distress message in OpenCPN

5.2 Power consumption

The power consumption is measured with a source measurement unit (SMU) from Qoitech. The manufacturer of the SMU states an accuracy of $\pm(1\% + 0.5\mu\text{A})$ [39]. For all the current draw measurements in this section, the supply voltage was 2.8 V, and the SMU was calibrated before each measurement. In addition to measuring power consumption, the data from these measurements can be used to identify the different tasks performed by the system, and their timing. This is especially useful for finding the acquisition time of the GPS module.

Figure 5.3 shows the current draw of the system while inactive. The average current draw is 58 nA. This value is too low to be accurately measured by the SMU. The worst case value can be calculated from the accuracy of the SMU to be 58 nA $\cdot 1.01 + 0.5$ μA$= 559$ nA. For a period of 10 years, this worst case value would add up to 49 mAh, and the measured value of 58 nA would add up to 5 mAh.

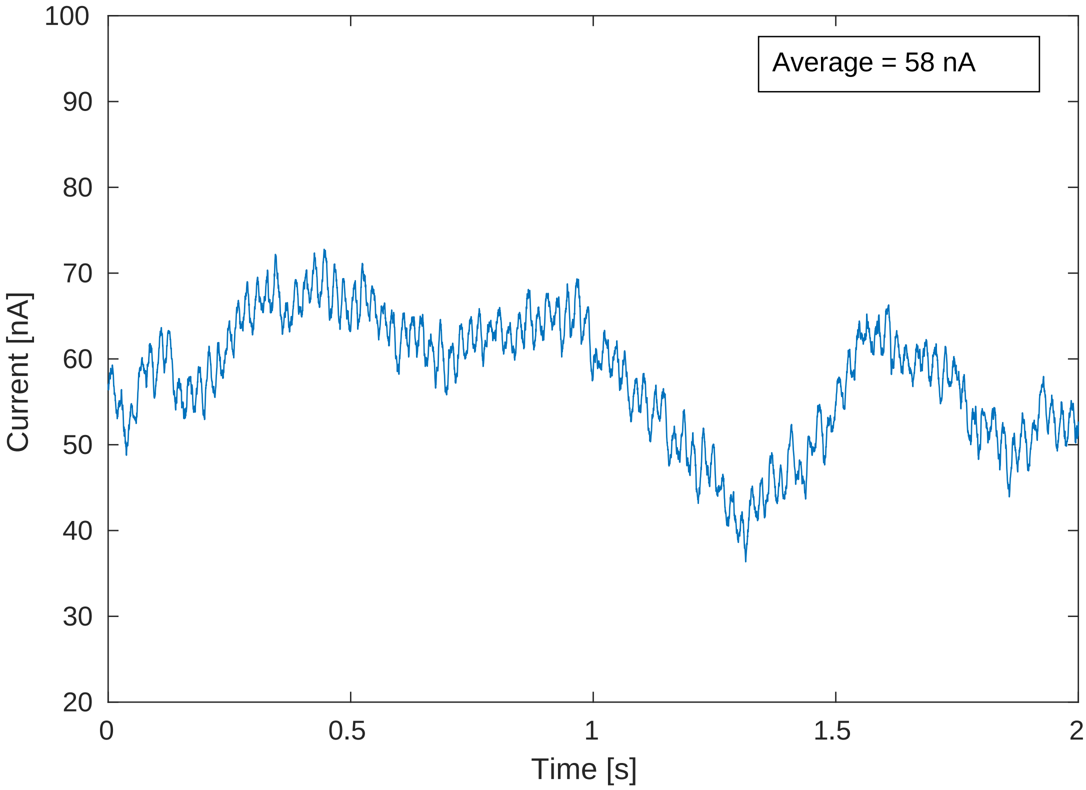


Figure 5.3: Power consumption wile inactive

Figure 5.4 shows the current draw of the system just after activation and until the first burst of AIS messages are sent. The acquisition time for position data, in this case, is about 58 s.

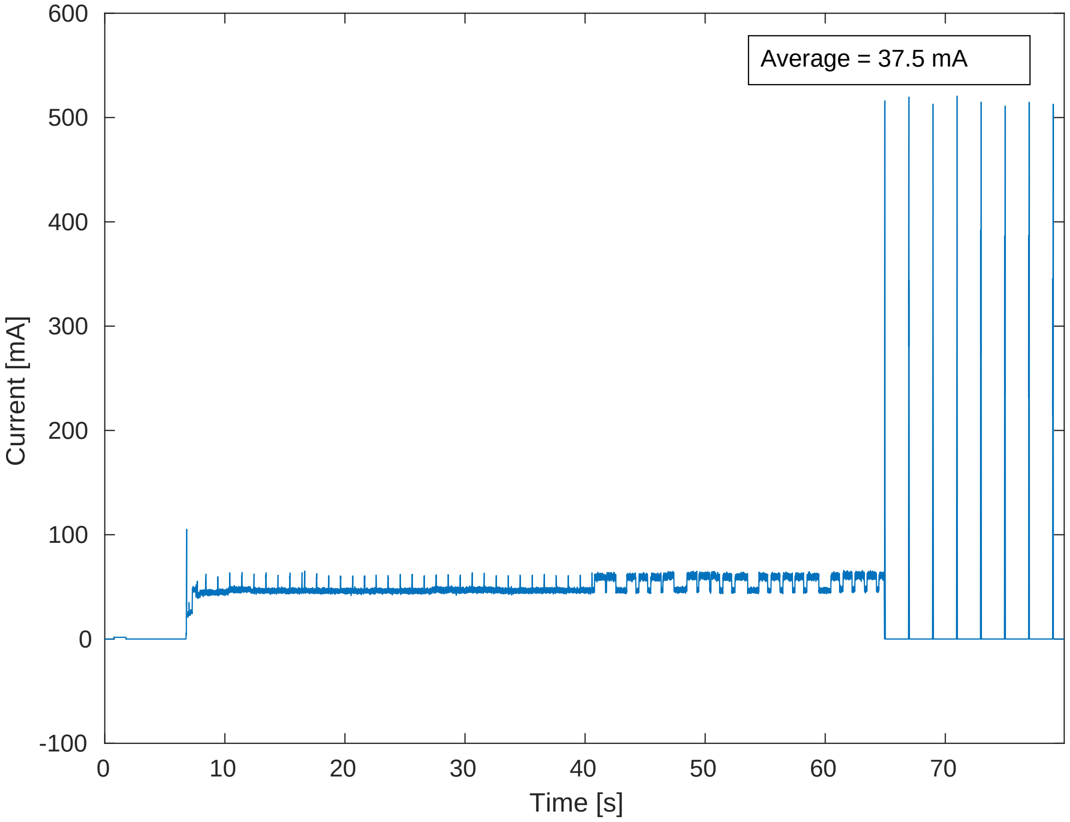


Figure 5.4: Power consumption at startup

Figure 5.5 shows the current draw of the system while active in a duration of six minutes. The bursts of eight spikes correspond to the system sending AIS messages, and the period following just after the bursts is when the system is updating the position data. The flat periods in between is when the system is sleeping. The current consumption while the system is sleeping is about 6 µA, and the current peaks are a bit over 500 mA while sending. The power consumption from GPS acquisition represents about 84 % of the average current draw here. The average current draw for the data in Figure 5.5 is 11 mA. The average time for the GPS reacquisitions is 13 s. The reacquisition time of the GPS was found to vary between tests, but the values presented in Figure 5.5 was found to be quite typical.

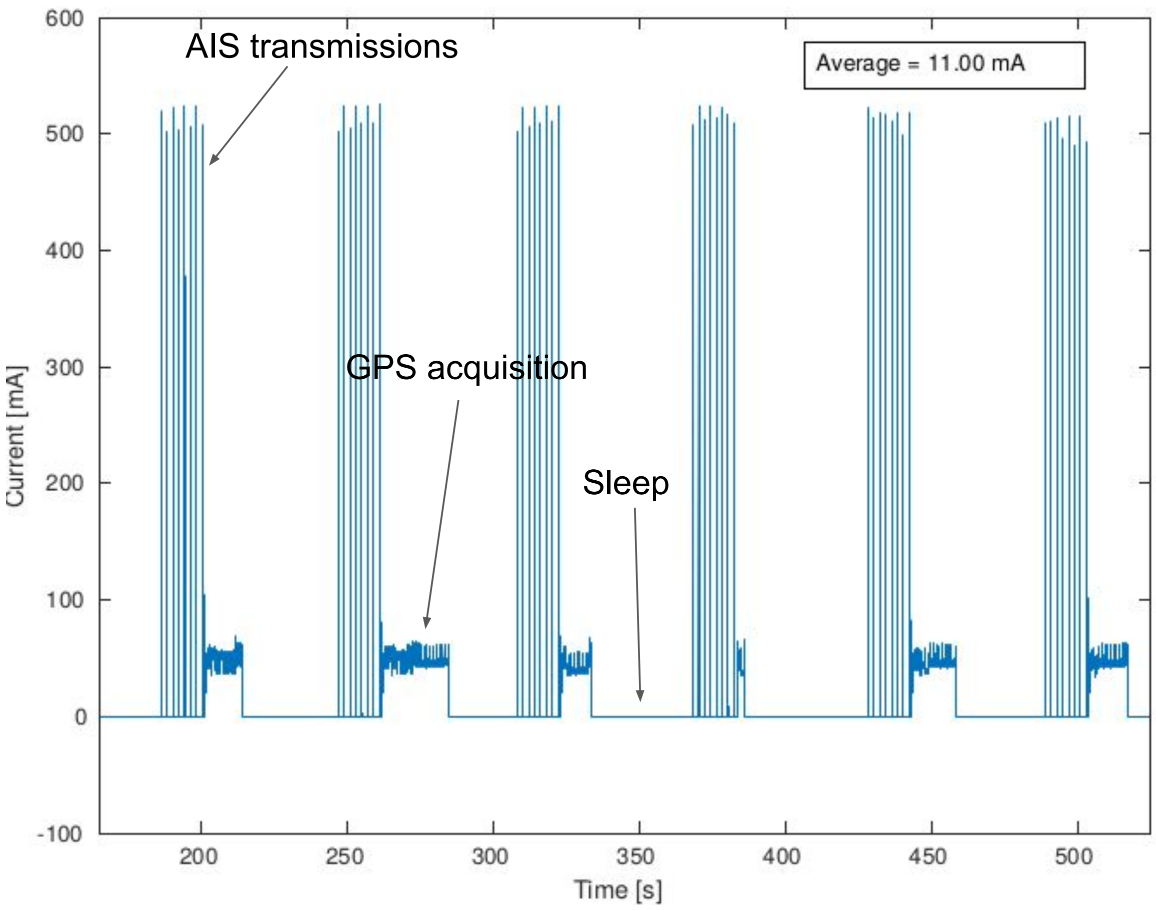


Figure 5.5: Power consumption while active

Figure 5.6 shows the current draw of the system in a period where it had lower GPS reacquisition time. In this case, the average GPS reacquisition time was 4 s, and the current draw from the GPS corresponds to 59% of the total consumption. The average current draw, in this case, was 4.81 mA. Through a series of tests, this was the lowest achieved average consumption, and thus it is not a representative value.

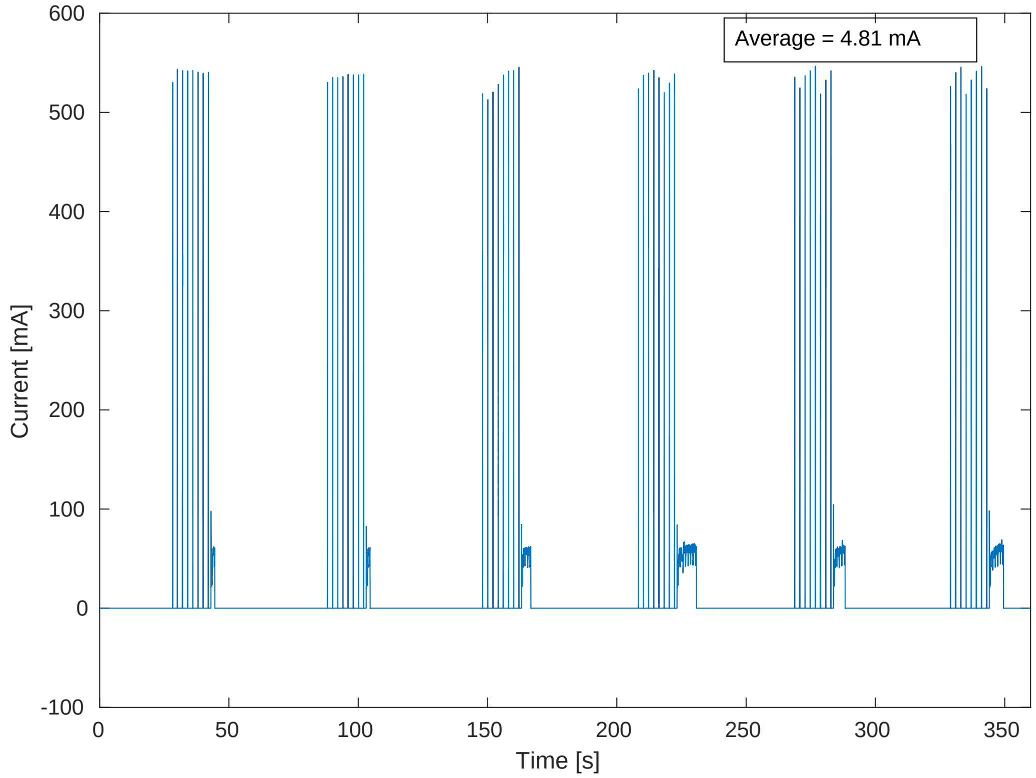


Figure 5.6: Power consumption while active in good conditions

If it is assumed that the current draw stays constant, the battery is full, and that the entire 1500 mAh capacity of the battery can be used, the operating time, T_O, of the system can be estimated. To make these estimates the estimated 0.45 mAh current draw from a LED indicator is added to the measured values. In the typical case, the estimated operating time becomes

$$T_{O_{typical}} = \frac{1500\text{mAh}}{11\text{mAh} + 0.45\text{mAh}} = 131\text{h}$$

The same estimate based on the best achieved current consumption becomes

$$T_{O_{best}} = \frac{1500\text{mAh}}{4.81\text{mAh} + 0.45\text{mAh}} = 285\text{h}$$

5.3 Output spectrum and power

The near spectrum of the system is measured with the SDR. Figure 5.7 shows the spectral density of a received signal, compared with the theoretical value found from equations 2.2.1 and 2.2.3. This figure also includes a spectrum mask, which shows the limits that the spectrum should be within [18]. All the spectrum values are normalised so that the peak value is at 0 dBc. In this measurement, the average power of a period with no transmission was used to find the receiver noise floor. From the figure, it can be seen that the transmitted signal closely resemble the theoretical values and that it is within the limits of the specification. A slight dip can be seen in the measured values at an offset around 2.4 kHz, this can be explained by an unequal amount of the two symbols, which can also be seen in Figure 5.1.

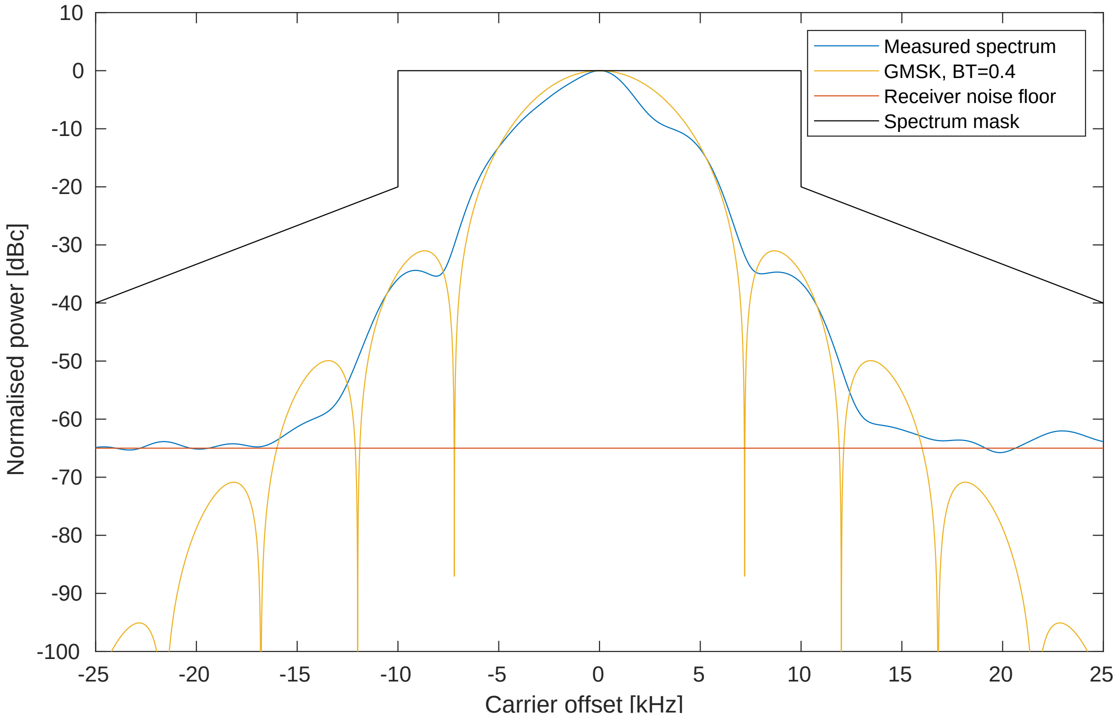


Figure 5.7: Spectral density comparison of theory and measurements

To measure the output power and harmonics of the system, the FSQ 40 signal analyser from Rohde & Schwarz is used [40]. This measurement is performed both with and without the PA. Figure 5.8 shows the measurements without the PA, where the output power is set at 11 dBm. When measuring with the PA, a total of 22 dB attenuation was used. Figure 5.9 shows the measurement with the PA. Compensating for the attenuation, the output power of the fundamental frequency reaches 29 dBm. The first harmonic frequency is 20.5 dB lower than the fundamental.

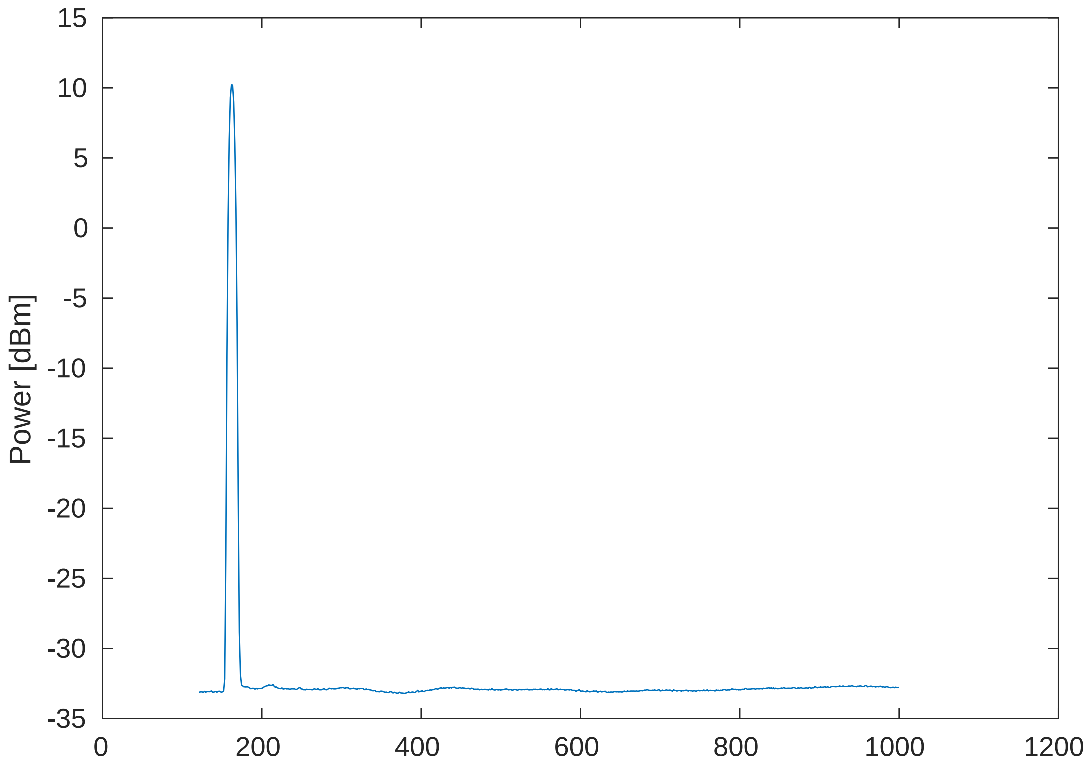


Figure 5.8: Output power and harmonics without PA

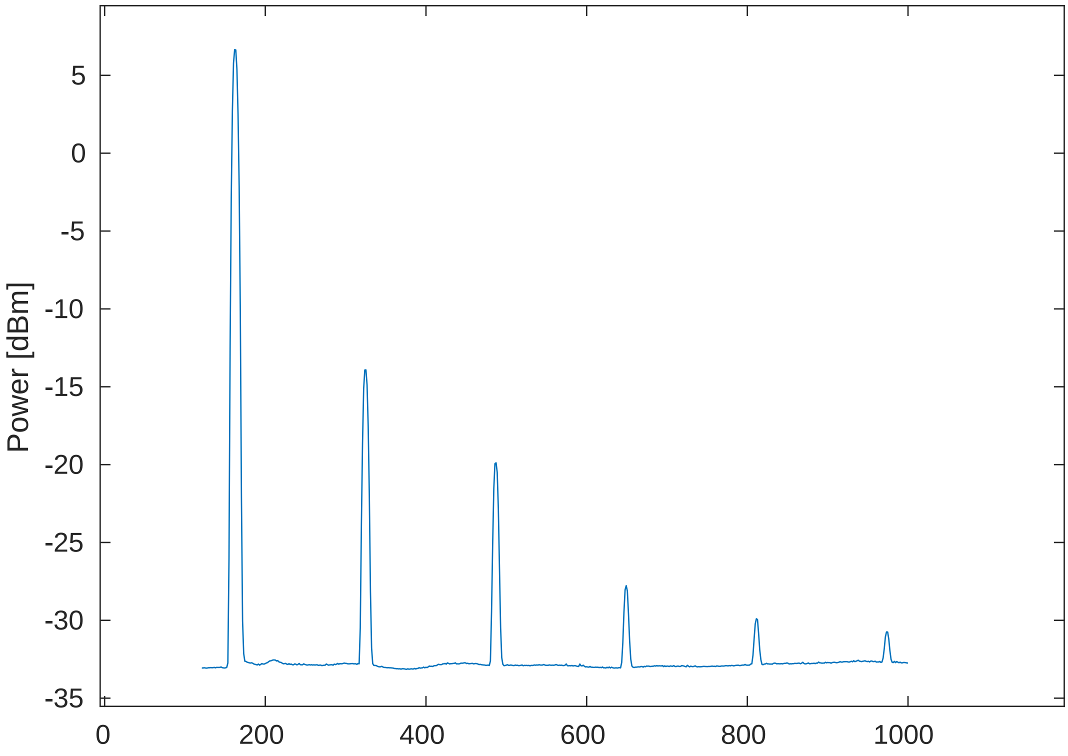


Figure 5.9: Output power and harmonics with PA and 22 dB attenuation

Chapter 6

Discussion

6.1 General operation

In the tests performed, it was shown that the system was capable of communicating with existing AIS equipment and correctly indicating the position of personnel fallen overboard. The water detection system was found to work as expected, although this was more proof of concept than rigorous testing.

6.2 RF power and spectrum

The near spectrum of the system showed a close resemblance to the theoretical values for GMSK modulation, and was within the limits set by applicable standards. The system without the PA performed as expected, and showed no sign of harmonics distortion. These tests showed that the correct modulation for AIS transmissions was achieved with the system used.

The power amplifier did not perform satisfactorily. The maximum achieved output power was 29 dBm, which is in the range of the ERP values from specifications, but it leaves no room to compensate for antenna efficiencies. In addition, the output spectrum after the PA showed relatively strong harmonic distortion with a second harmonic 20.5 dB lower than the fundamental. Still, the output power is close to the desired value, and comparisons with other work should not suffer dramatically from this reduced output power.

6.3 Size and power consumption

The power consumption of the device when inactive was found to be negligible, meaning that the limiting factor for the battery change cycle is determined by the shelf life of the battery itself, which is 10 years.

When the device is active, it was found that the power consumption of the device is highly dependant on the acquisition time of the GPS. In general, the GPS module was found to perform significantly worse than the stated values in the datasheet. The best average current draw when active was found to be 4.81 mA and a more representative value was found to be

11 mA. In both of these cases, the power consumption from the GPS module represented more than half of the total power consumption. Based on these measurements, estimates of the operating time of the system was made. These estimates made some assumptions, but these assumptions were the same ones used in the work of Y. Li et al [3]. This means that comparisons with that work should be valid. Table 6.1 compares this work to some of the existing work described in Chapter 1.3. The active current draw used in this table is based on the typical value found in the results, with the added estimate for the current draw of an LED indicator.

Table 6.1: Comparison of this work and state of the art

	This work	**Y. li et al. [3]**	**Ocean signal MOB1 [6]**
Battery change cycle	10 years	-	7 years
Operation time	131 h	36 h	24 h
Battery voltage	3 V	6 V	6 V [4]
Battery capacity	1500 mAh	2400 mAh	1500 mAh [5]
Active current draw	11.45 mA	66.6 mA	-
Size	19x26x67 mm	22x45x118 mm	27x38x134 mm
Weight	34 g	100 g	92 g

When compared to existing solutions, the size and the power consumption of the designed system shows significant improvements. When compensating for the difference in operating voltage, this work has less than $\frac{1}{10}$ of the power consumption of the work of Y. Li et al. One likely contributor to the reduction in power consumption, is the choice to go for a different system structure. In this work, a general purpose radio transmitter was selected, which had significantly better power consumption characteristics than the alternative specialized AIS hardware used by other work [22] [19]. Other contributing factors are that all the other parts of the system were chosen with low power consumption in mind, and the system was designed such that no regulator is active during the system's idle state.

The comparisons made should, however, be taken with a grain of salt, as the designed system is not complete. The key points that lower the accuracy of the comparisons can be summed up as:

- No visual indicator was included in the design, the power consumption of this was instead estimated.
- The maximum output power of the system was 29 dBm, which is lower than that of some of the other solutions.
- No antenna and mechanical packaging were included in the size and weight measurements.

6.4 Future work

As discussed in Section 3.4.1, there are several possible antenna solutions that should be explored. An especially interesting approach would be to place the antenna on the inside of a life-jacket.

The PA designed in this work should be redesigned, it lacked the required output power, and it added harmonic distortion to the output signal.

If further reduction in power consumption is desired, different GPS solutions should be explored. Even under the best GPS conditions tested, the power consumption from the GPS module amounted to more than half of the overall power consumption. The GPS solution is therefore believed to be the best candidate for further reduction of power consumption.

The selected battery was one of the main contributors to the overall size. Additionally, the operating time of the system was excessively long, meaning that there is room for reducing the battery capacity and size. Smaller battery solutions should be looked at to further reduce the size of the system.

Chapter 7

Conclusion

This thesis has presented a proposed design and implementation of an AIS MOB beacon meant for life jacket integration. The primary goal for enabling full integration in life jackets was to reduce the overall size of such devices. The main means of achieving a reduction in size was to reduce the power consumption of the device and therefore minimising the battery pack. The design of such a device spans over several different disciplines, and the different subsystems showed performance with varying success. The system was capable of sending correct AIS MOB messages and worked well with existing AIS equipment. An effort was made to compare this work with state of the art MOB devices, and although the accuracy of these comparisons can be discussed, the designed system shows good promise in reducing the size and power consumption of such devices. Most notably, the designed system consumes $\frac{1}{10}$ less power than a similar system described in recent literature.

A key factor for achieving this reduction was to use modern ultra-low-power general hardware for the generation of the AIS radio signals. The choice of general hardware resulted in an increase in the complexity of the firmware design. Other key factors included choosing each component in the system with low power consumption in mind, keeping the number of components to a minimum, and minimising the inactive current draw of all submodules by gating their access to power.

The designed system should provide a good starting point for the design of a fully life jacket integrated AIS MOB device, but further work is necessary to achieve this. The overall size and power consumption reductions is believed to be satisfactory, but solutions for antenna integration needs to be further investigated.

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Appendix A

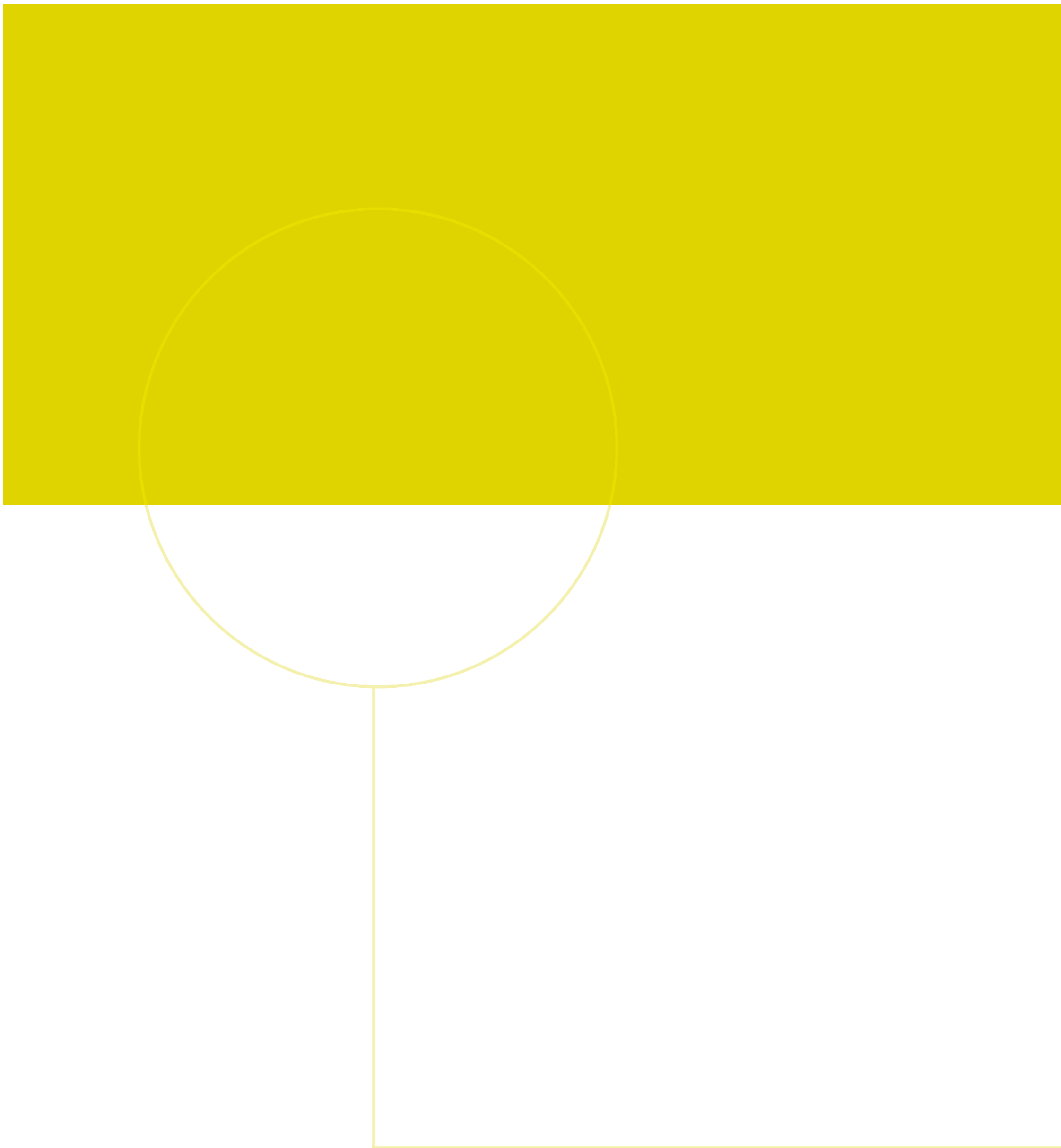
AIS messages 1 and 14 content

A.1 AIS messages 14 content

Parameter	**Bits**	**Description**
Message ID	6	Identifier for message, 14 for this message type
Repeat indicator	2	Indication of how many times a message has been repeated
User ID	30	MMSI number
Spare	2	Not in use, set to zero
Safety related text	Maximum 968	6-bit ASCII, "MOB ACTIVE" for distress, "MOB TEST" for test
Number of bits	**Maximum 1008**	

A.2 AIS messages 1 content

Parameter	**Bits**	**Description**
Message ID	6	Identifier for message, 1 for this message type
Repeat indicator	2	Indication of how many times a message has been repeated
User ID	30	MMSI number
Navigational status	4	Describing activity. 14=AIS SART/MOB active, 15 = AIS SART/MOB under test
ROT	8	Rate of turn. Not used in this work
SOG	10	Speed over ground, 1/10 knots. 1023 = not available
Position accuracy	1	0 if >10m, 1 if <10m
Longitude	28	Two's complement. 1/10000 minutes. posetive = East, negative = West. 181 deg = not available
Latitude	27	Two's complement. 1/10000 minutes. posetive = North, negative = South. 91 deg = not available
COG	12	Course over ground in 0.1 degrees. 3600 = not available
True heading	9	Heading in degrees. 511 = not available
Time stamp	6	UTC second when message was generated. 60 = not available
Special manoeuvre indicator	2	0 = not available, 1 = not engaged in special manoeuvre 2 = engaged in special manoeuvre
Spare	3	Not in use, set to zero
RAIM-flag	1	Receiver autonomous integrity monitoring (RAIM) flag of electronic position fixing device. 1 = RAIM in use, 0 = RAIM not in use
Communication state	19	Communication state for SOTDMA handling. Not fully implemented in this work
Number of bits	**168**	



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