Design of a low power AIS MOB beacon for life jacket integration

Master thesis

Amund Askeland

Supervisors:
Egil Eide, NTNU
Per Christian Berntsen, AISTech

Fall 2018

Norges Teknisk-Naturvitenskapelige Universitet
Institutt for Elektroniske Systemer

Contents

List of Figures

List of Tables

1 Abstract

2 Introduction

2.1 Topic

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 over board. In recent years the AIS protocols has 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. When such a device is activated, it will acquire its position and send AIS messages to nearby ships notifying them of the situation. Personnel falling over board from ships can be very hard to locate, and given that time in these situations are very limited, MOB devices transmitting a distress message with the location of the personnel over board can be the difference of life and death.

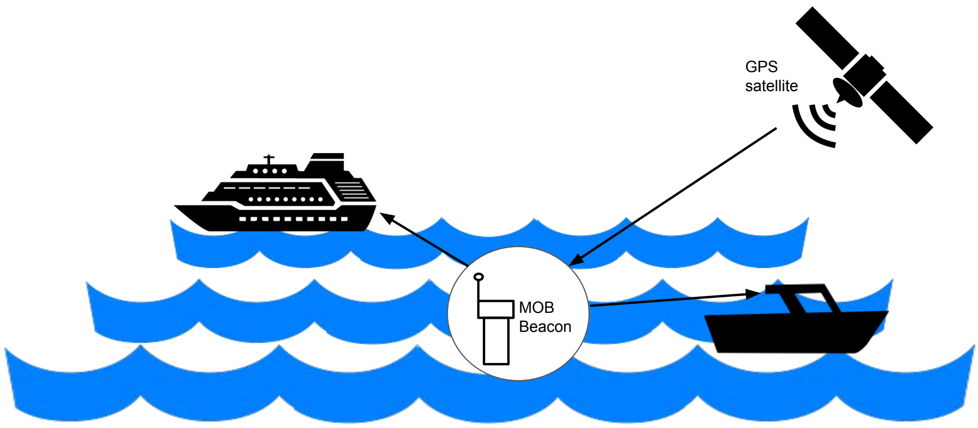

Figure 1: AIS MOB device concept

2.2 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 is shown in figure 2.

Figure 2: Mob beacons from various manufacturers, reproduced with permission from Panbo [1]

2.3 Problem solution

By integrating the MOB device into the life jacket, the MOB device would no longer be a hindrance, and it would potentially result in a increased usage of such devices. There are several challenges that needs to be addressed for this to become a possibility. 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 a lower power consumption. The goal of this work is to look into the feasibility of integrating

MOB devices into life jackets. While one way to investigate this would be to look at the individual subsystems that make up such a system individually, this work will based around designing a prototype. Designing a prototype of the complete system has the advantage of showing a working interaction between the subsystems, as well as being a better way to show the achievable performance and size of such a system. The proposed design will however not necessarily be a finished product, and might take some shortcuts. If satisfactory results can be achieved, this work would propose a design that enables easy integration into life jackets.

Designing the electronics of such a device is a multi-disciplinary task spanning over many disciplines including software design, digital communication, RF-circuitry design, and low-power embedded design. AIS equipment uses two VHF-band channels, and Gaussian minimum shift keying for modulation. Part of the challenge will be to design the system such that it complies with the AIS-standard and can communicate with existing AIS equipment.

3 Background

3.1 Low power design techniques

When designing low power embedded systems, a large part of 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 utilise these components in the correct way. 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 section will take a look at common power saving techniques in MCUs, and the application level usage of these, as well as system level power saving techniques.

3.1.1 Application level power saving techniques in MCUs

MCUs are good examples of devices where the designers often 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 [4].

- 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 above 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 such as SPI and UART, 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 is 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 [5] [6] [7].

3.1.2 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 has to be introduced into the circuit. This leads to increased power consumption, since no regulators have 100% efficiency.

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.

3.2 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.

3.2.1 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 3. 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 means that the channel bandwidth increases, which can lead to interference with neighbouring channels.

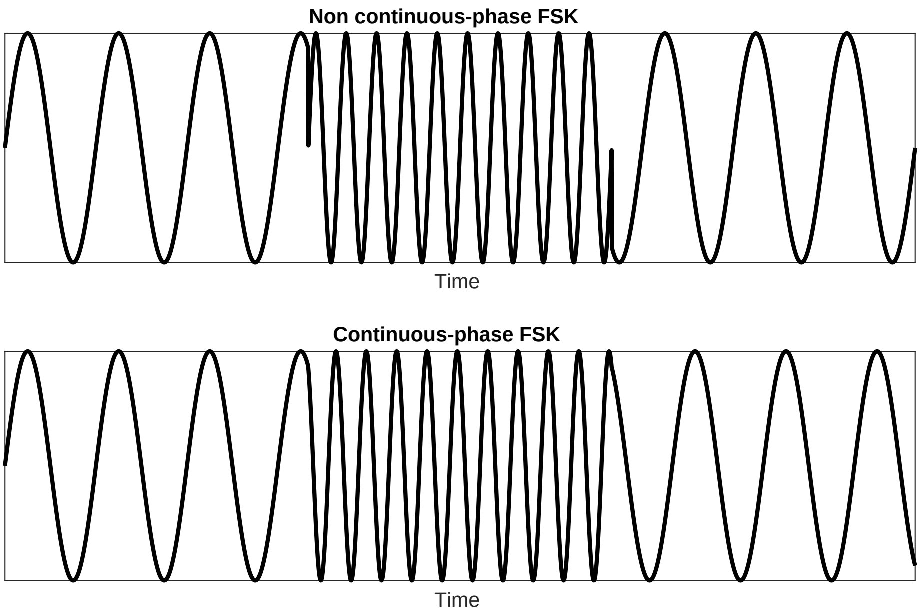

Figure 3: FSK modulation with and without continuous phase

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 distinguishing them. For continuous-time signals, the correlation, $\langle x(t), y(t) \rangle$ can be written as below.

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

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 $\frac{1}{2T_s}$, where T_s is the symbol duration. [8]. 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. However, 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. It can be shown that this degradation is not severe for filters that are not too aggressive [9]. This Gaussian premodulation filter has an impulse response given by equation 3.1, and a transfer function given by equation 3.2. The parameter α is related to the 3 dB baseband bandwidth of $H_G(f)$ by equation 3.3 [9].

$$h_G(t) = \frac{\sqrt{\pi}}{\alpha} \exp\left(- \frac{\pi^2}{\alpha^2} t^2 \right) \tag{3.1}$$

$$H_G(f) = \exp(-\alpha^2 f^2) \tag{3.2}$$

$$\alpha = \frac{\sqrt{\ln(2)}}{\sqrt{2} \cdot B} \tag{3.3}$$

The GMSK premodulation filter can then be completely defined from B and the symbol duration T, this is usually referred to as the Bandwidth-Time product, or the BT-product. Figure 4 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 an increased inter symbol interference.

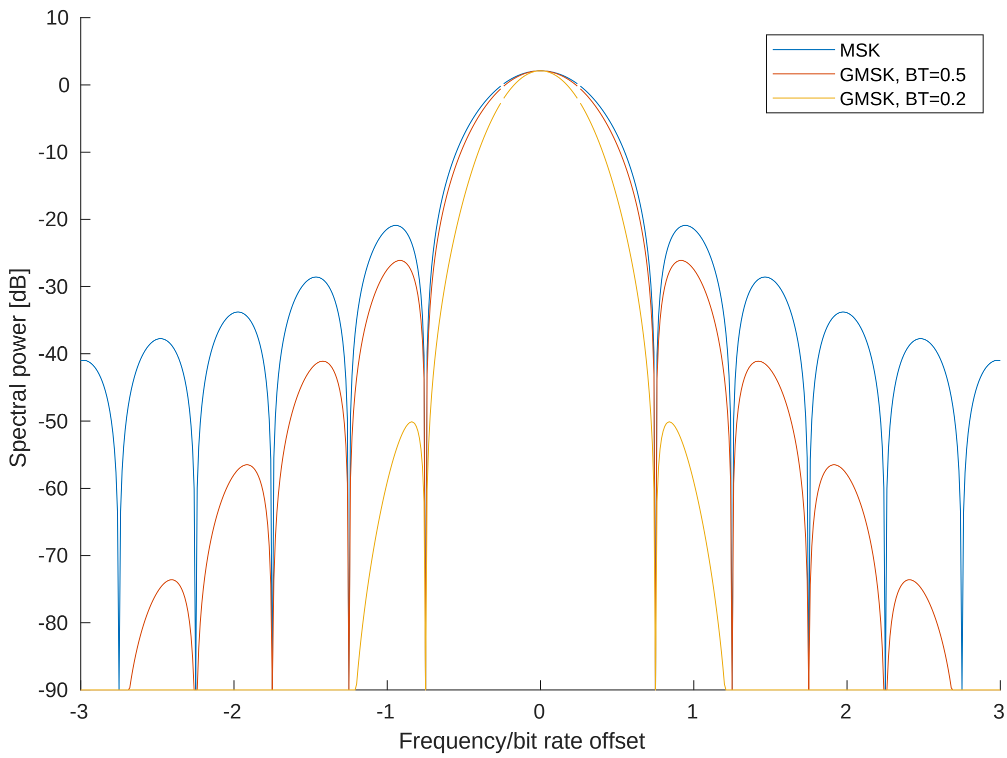

Figure 4: Spectral power comparison of MSK and GMSK

4 AIS specifications

The automatic indentification system (AIS) was introduced by the International Maritime Organisation (IMO) to increase the safety of ships and the invironment, and to improve traffic monitoring and maritime traffic services.

4.1 Physical layer

AIS operates on two channels in the VHF band, refered to as channel 1 and 2, the center frequencies for these channels are respectively 161.975 MHz and 162.025 MHz. AIS messages are transmitted using GMSK modulation with two symbols. The BT-product of the pre-modulation filter is 0.4 [10]. The data rate used by AIS is 9600 bit/s and the frequency deviation is 2.4 kHz. This satisfies GMSK modulation as discussed in section 3.2.1.

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 [10]. Figure 5 shows an example of this encoding scheme.

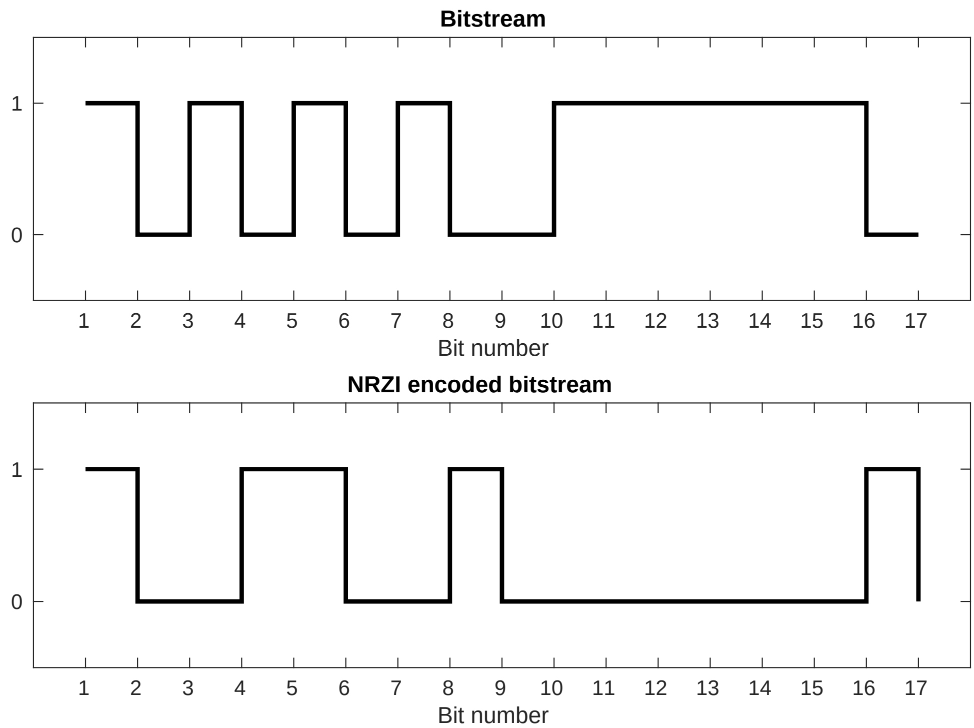

Figure 5: NRZI encoding

Figure 6 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.

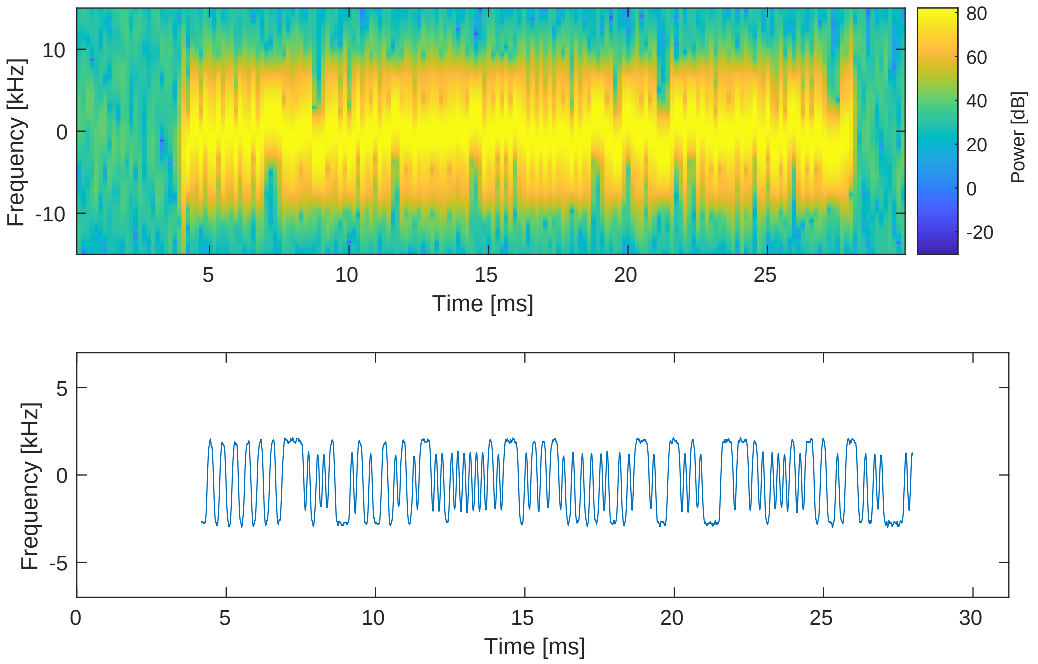

Figure 6: Captured AIS message from ship

4.2 Link layer

The AIS messages are build up as shown in figure 7. The first 24 bits is a preamble, which is a series of alternating ones and zeros than can start with either a one or zero. The next field is a 8-bit start flag indicating the start of a message. The value of the start flag is 0x7E. 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. 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 6.

The last field shown in figure 7 is a buffer which is not an actual field that is sent, but a it serves several important purposes. These purposes include compensation for distance delay and synchronization jitter, as well as bit stuffing [10] which will be looked more closely.

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

Figure 7: 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 scheduled position report, and message type 14 which is a safety related broadcast message. The content of these messages are described appendices A.1 and A.2 [10]. 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.

4.3 Time slot handling

AIS uses self organized time division multiple access (SOTDMA) to distribute access to the transfer medium (i.e the AIS channels) [10]. 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 datarate 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, needs to indicate this in the transmitted data. Such equipment should still indicate the next slot that it intends to use.

4.4 AIS MOB beacon operation

AIS MOB beacons that wish to comply with regulatory standards, should follow the standard described in the ETSI EN 303 098 [2] document. 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.

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 burst 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 8 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.1 and A.2 [10].

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.

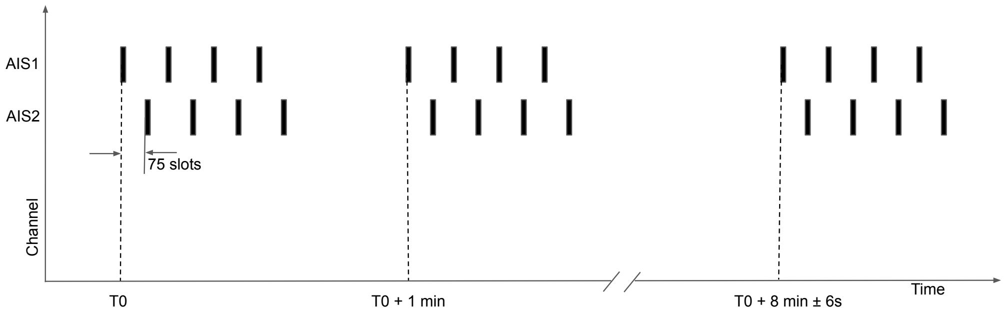

Figure 8: AIS MOB burst operation [2]

5 State of the art

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 2. The rescueME MOB1 is currently marketed as *"The worlds smallest personal locating AIS Man OverBoard device with integrated DSC"* [11].

In addition to commercially available products, Y. Li et al. described the design of an AIS MOB device in a published article [12]. In that work, the authors states than 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 [13] [14]. 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 compares some important parameters of existing products, with respect to size and power consumption.

Table 1: Comparison of existing work

	Y. li et al. [12]	**Ocean signal MOB1 [15]**	**Kannad R10 [16]**
Battery change cycle	-	7 years	7 years
Operation time	36 h	24 h	24 h
Battery voltage	6 V	6 V [13]	6 V
Battery capacity	2400 mAh	1500 mAh [14]	-
Size	22X45X118 mm	27X38X134 mm	27X47X124 mm
Weight	100 g	92 g	120 g

6 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 1 W of radiated power
- 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.

6.1 System overview

The design will be described on a high level by drawing a block diagram of the required modules, as well as drawing a flow chart for the code of the system. To draw a block diagram, the main required system parts has to be identified. At the heart of the system an MCU is needed to control the rest of the system. This MCU will be responsible for taking in information from other parts of the system, and it needs to be able to generate AIS messages, that can be sent by a different part of the system. In order to acquire the position of the device, a GPS module is also needed. Another necessary component is a transmitter, that is capable of receiving commands from the MCU, and generating correct RF signals based on those commands. Since there are strict restrictions on transmitted power in most bands, it is unlikely to find a transmitter that can send at the required 1 W of output power, and therefore a power amplifier (PA) is also necessary. At the end of the RF part of the system, an antenna is needed. Means of detecting water, and a test button is also required to initiate the system. Finally, a power source is required. Figure 9 shows a block diagram of the described modules. Each of the blocks will be looked into in more depth to determine the components that will be used.

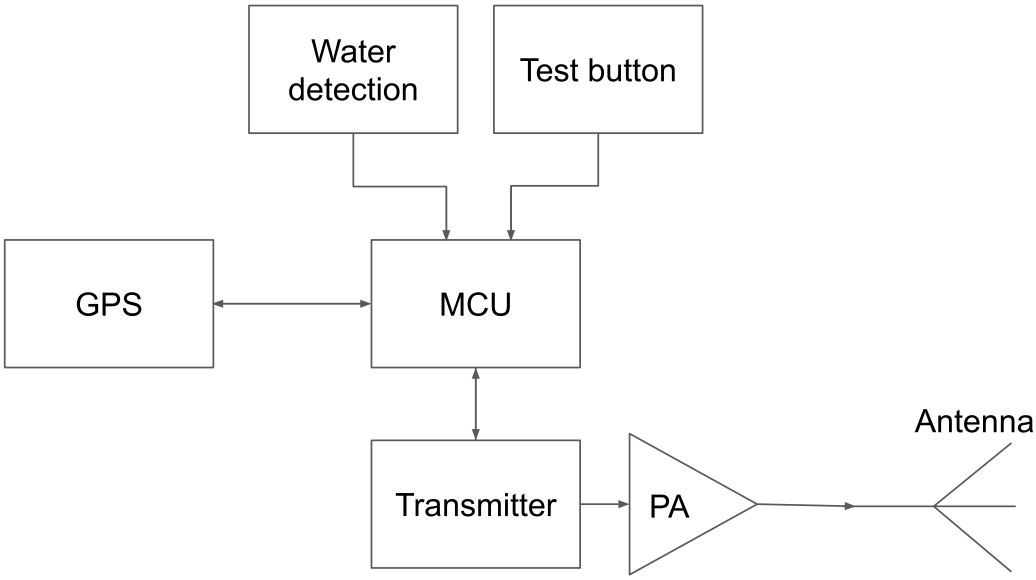

Figure 9: System block diagram

6.2 Component selection

While the necessary modules are described in figure 9, choices for the actual components are still to be made. This section will discuss 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.

6.2.1 Transmitter

To the authors knowledge, the only company producing dedicated SART/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 10 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 [17].

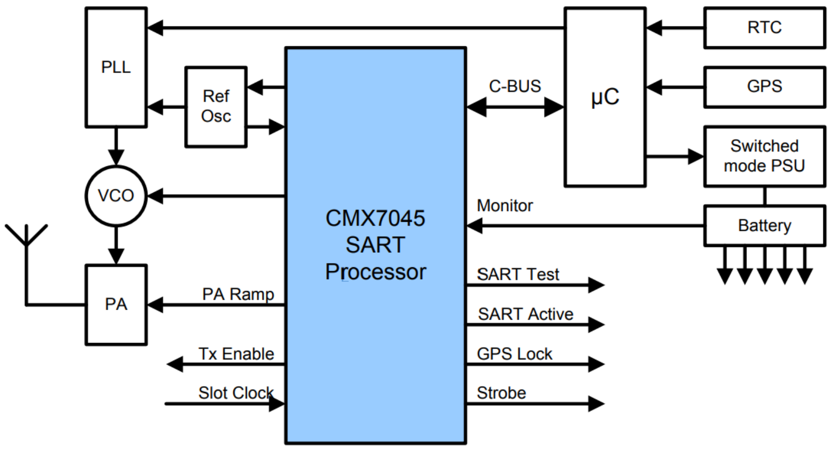

Figure 10: CMX7045 proposed system diagram, reproduced with permission from CML [3]

The alternative to using a special purpose AIS device, is to use a general purpose transmitter. While there are many products that 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 3.1.2, 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 et cetra. This could again suggest a shorter design time.

The choice is now narrowed down to either the special purpose AIS SART 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 a shorter design time and less complexity in the code. Selecting the general purpose transmitter means that many parameters including the exact modulation and generation of the signal needs to taken into consideration in the software design. This is no obvious choice to make, but 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 a device from the Si446x series. The design goals of low power consumption and a small size needs to take precedence over the design time.

6.2.2 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 manufactures. 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 for many peripherals. However the MCU will have to communicate with other devices, so hardware implementations of common on board communication protocols such as SPI, I2C and UART 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 a transceiver from the Si446x series [18]. This means that the transmitter part of the system can be combined with the MCU in one single device. This device can achieve a power consumption of 20nA while inactive [19], and the transmitter part of the system has otherwise the same performance as described in the previous section.

6.2.3 Power amplifier

The chosen transmitter has a selectable power output of up to 20 dBm, while the finished system should have an output power of 1W or 30 dBm. 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 2W/33dBm 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 be 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 especially 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.

6.2.4 Antenna

The antenna solution for this system quickly becomes a challenging design process with respect to the mechanical design. For this reason, no particular antenna will be chosen in this design. Instead the output power will be measured 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.

6.2.5 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 to reduce the need for regulators, it would have a low current consumption, and it would have a simple and efficient interface. The interface that most such modules seems to be the NMEA specification sent over UART at a fixed rate. This type of interface is based on sending data as ASCII encoded strings, which is a general way of sending data that can be used by many different systems. However this is far from an ideal way to send data for energy efficient systems. An example of NMEA output from a GPS module is shown below. Each of the characters are sent as ASCII values, including each of the digits of the position.

```
$GPRMC,092750.000,A,5321.6802,N,00630.3372,W,0.02,31.66,280511,,,A*43
```

After comparing several types of GPS modules, the L80 from Queltec was found to be a decent choice. This device has a comparatively low price, relatively low power consumption of 25 mA when acquiring position data, and a backup mode where it consumes 7 μA. The backup mode is a mode where previously data is stored, while a low frequency timer is active to keep track of time. This reduces the time for the next position acquisition [20].

6.2.6 Battery

Choosing a battery for this design might not be most challenging part of the design, but it is a task that should definitely 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 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, voltages well above what can be used by the selected MCU, and this is not a device 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 [21].

6.3 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 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 system design. While the power consumption is the measure of interest, it is often helpful to think about the current draw in stead. 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.

6.3.1 Inactive mode

In inactive mode, the 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 [19]. 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 decouple 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 [21].

6.3.2 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 first time the GPS wakes up, a typical time to acquire position is 35 s according to the manufacturer. If the GPS' backup power is supplied after this, the subsequent attempts to acquire position should typically take 5 s. The manufacturer of the GPS module states a typical current draw when acquiring position of 25 mA, and 7 µA when in backup mode. In order to supply the GPS module with a constant 3.3 V source, a regulator is used. An efficiency of 70% can be used for this regulator, and since the consumption is calculated as current consumption, the value should be further divided by $\frac{3.3}{V_{dd}}$, where 2.8 could be used as an average V_{dd}. In section 4.4, 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 From this, the average current draw can be calculated as follows.

$$\frac{25\text{mA} \cdot 5\text{s} \cdot \frac{3.3\text{V}}{2.8\text{V} \cdot 0.7}}{60\text{s}} + 7\mu\text{A} = 3.5\text{mA}$$

The manufacturer of the transmitter states a 69 mA power consumption at +20 dBm output power and 169 MHz [19]. 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 4.4, it was discussed that the system will send 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:

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

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 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. While well designed transistor amplifiers operating in class B can have efficiencies of 78.5%, things like imperfect matching, and imperfect biasing is likely to reduce this number. In addition, the selected amplifier transistor requires a rather high voltage of around 7 V, which will have to be sourced from a boost converter. This converter is likely to have an efficiency of around 90%. In total, an estimate of around 50% DC to RF efficiency can be used for this estimate. The estimated average current draw from the PA then becomes as follows.

$$\frac{8 \cdot 30\text{ms} \cdot \frac{1\text{W}}{3\text{V}} \cdot \frac{1}{0.5 \cdot 0.9}}{60\text{s}} = 2.9\text{mA}$$

The current draw from the MCU in active mode is highly dependant on the fix time of the GPS. The MCU has a current draw of about 1 µA while inactive, yet being able to wake up after a set time by using its internal low frequency timer. However, the chosen GPS has no means of waking the MCU when a position has been aquired, so the MCU needs to check every message coming from the GPS in order to find out. If this is timed well, the MCU can stay inactive, and wake up from the timer just before the GPS sends its UART messages. This is a hard estimate to make, but a very conservative estimate would be an average current draw of 1mA from the MCU when the system is active.

In summary, the different estimates can be added together to give an estimate of the total current draw of $3.5\text{mA} + 0.25\text{mA} + 2.9\text{mA} + 1\text{mA} = 6.65\text{mA}$. In the work of Y. Li et al [12], a similar system was designed, and the achieved average current draw in active mode was 66.6 mA. 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.

7 Implementation

7.1 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.

7.1.1 Transmitter

The SI4463 transmitter has an internal class-E amplifier with adjustable output power of up to +20 dBm [19]. 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 is 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 [22], 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 it's resonance frequency given by equation 7.1, 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 won't pass.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{7.1}$$

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 schematic of this part of the RF circuit can be seen in figure 11.

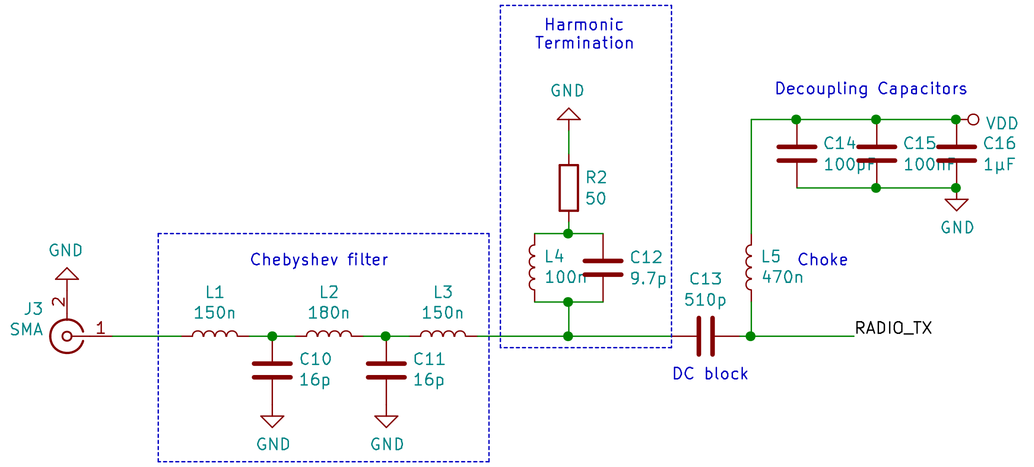

Figure 11: Schematic of output from transmitter

7.1.2 Power amplifier

The power amplifier design will be loosely based on a reference design from the manufacturer [23]. 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. Figure 12 shows the design, without specified values for the matching network. The specific values for the matching networks is obtained through a mixture of simulation and measurements using a network analyser. Figures 13 and 14 shows the scattering parameters of the unmatched circuit. From S_{21} it can be seen that the gain of the amplifier is satisfactory around 19 dB.

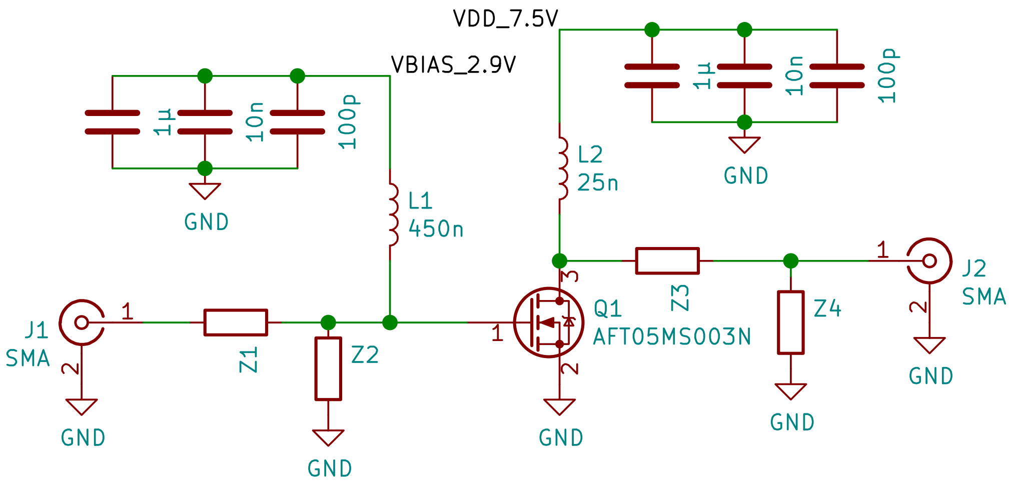

Figure 12: Amplifier schematic

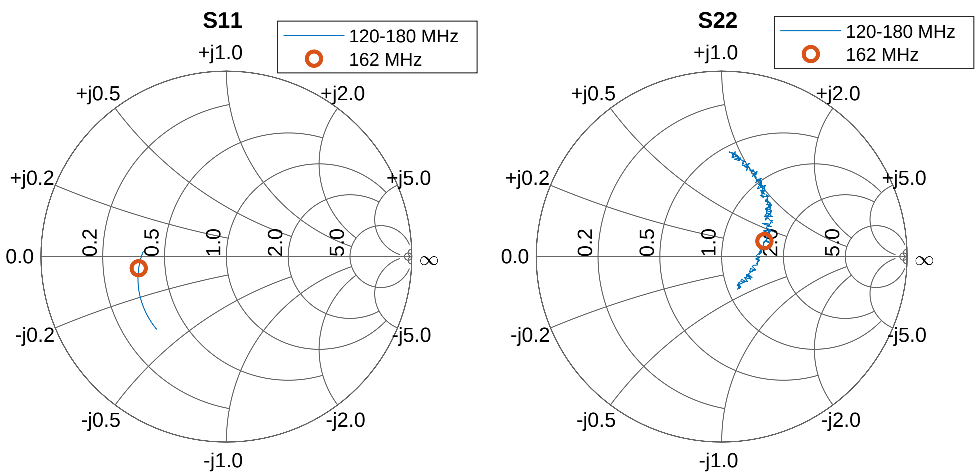

Figure 13: S_{11} and S_{22} of amplifier before matching

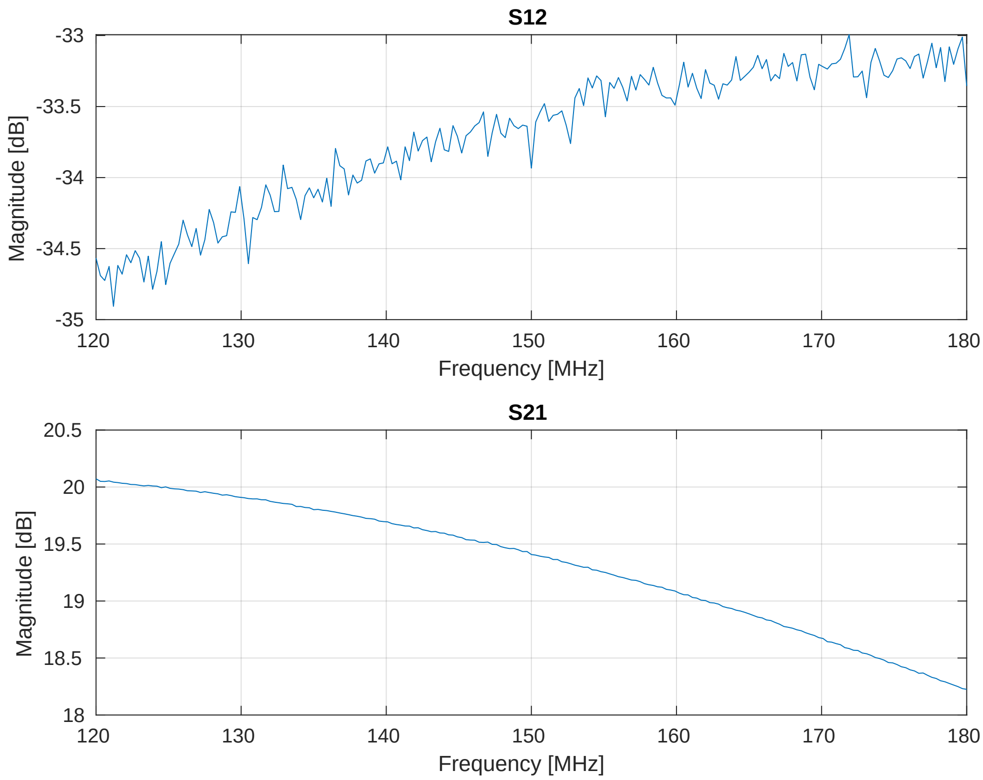

Figure 14: S_{12} and S_{21} of amplifier before matching

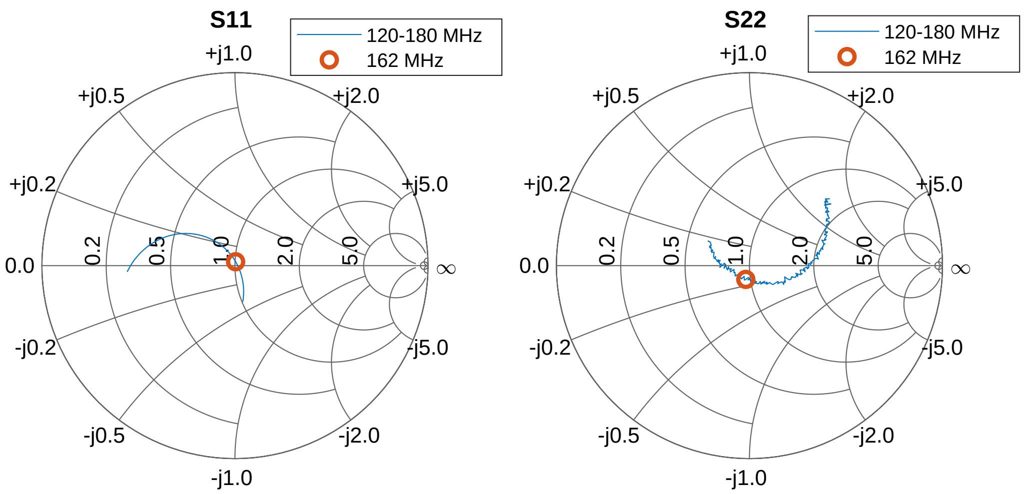

Figure 15: S_{11} and S_{22} of amplifier after matching

7.2 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 General Purpose Input Output (GPIO) pin of the EZR32. The EZR32 is capable of waking up from a very low power consumption mode refered 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 the 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 [19]. 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 16. The EZR32 considers inputs lower than $0.3 \cdot V_{DD}$ as logical low [19], 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 sea water are around 50 Ω^{-1}/m [24], which would result in a 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.

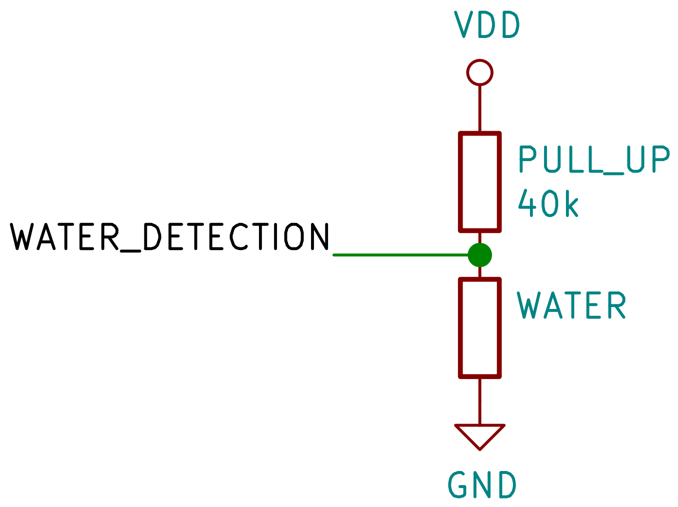

Figure 16: Water detection equivalent circuit

7.3 GPS hardware

The L80 GPS module requires an input voltage of at least 3 V, which means that a voltage regulator is required to supply power to it. In order to achieve this, without increasing the power consumption of the system when inactive, the voltage regulator is power gated with a p-type MOSFET. The backup circuitry of the GPS module has a separate supply, which can operate at voltages down to 1.5 V [20]. Since the backup current is low, this means that the backup supply voltage can be supplied (and controlled) directly from a GPIO pin of the MCU. Figure 17 shows a simplified schematic of the GPS supply circuitry.

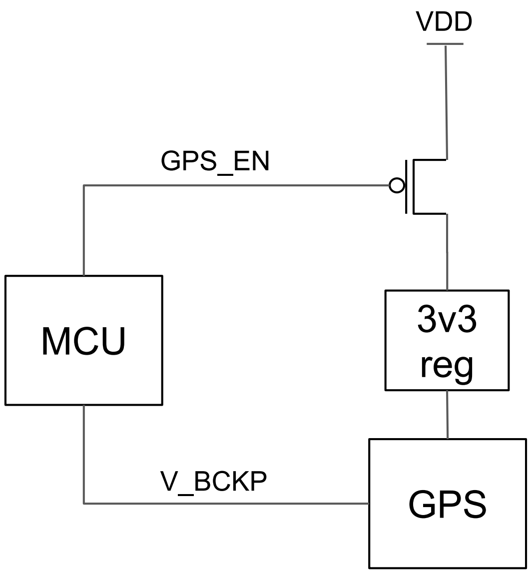

Figure 17: Simplified GPS supply schematic

7.4 Software

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 software design, as it needs to handle AIS message generation, AIS timing requirements, and the exact configuration of the radio transmitter. The software in this work will all be written for the EZR32 MCU, in the C programming language.

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 software 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 9 shows a high-level state digram for the software. This state diagram describes the main states, actions performed immediately upon entering the states, and the events causing state change. The state diagram shows how the system will enable and disable modules as they are needed. One thing to note from the state diagram, is that the 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.

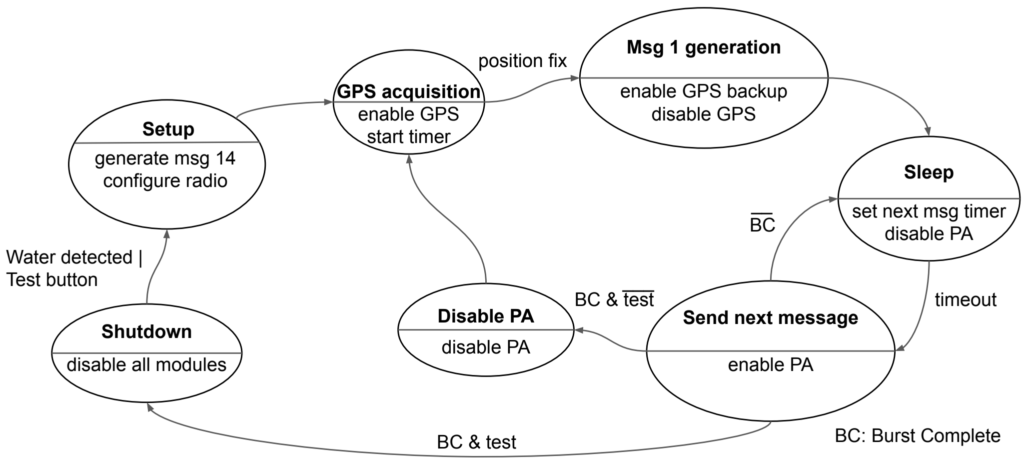

Figure 18: System state diagram

7.4.1 AIS message generation

Before AIS messages can be sent, they need to be constructed so that they comply with the protocol. Figure 7 in section 4.2 shows the different fields in an AIS message. The generation of AIS messages can be divided into several different tasks as shown in figure 19. In the software, 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, 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. 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 [2].

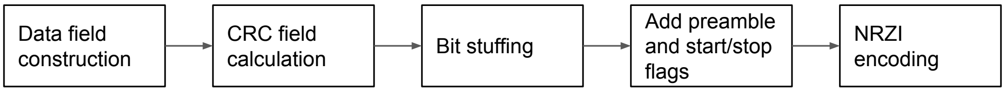

Figure 19: Code blocks for message generation

7.4.2 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 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 deviation, but not all the options are exposed in this program. Table 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 3.2.1, 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 in 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 2, except the BT product can be entered directly into WDS.

Table 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

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 [19]. 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 3.1. 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 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 is shown in figure 20.

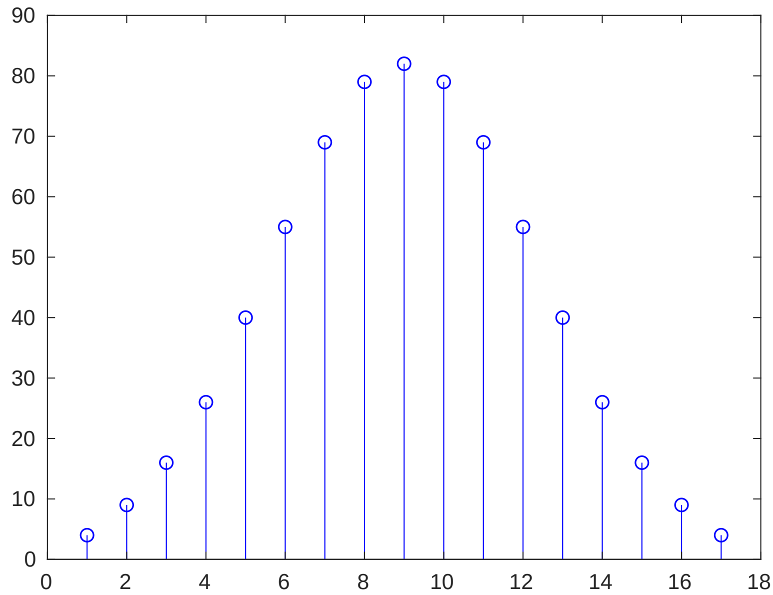

Figure 20: Gaussian FIR filter coefficients, BT=0.4

After getting the correct configuration register values, the software is written so that the radio is configured upon activation of the system. This is done via the transmitters SPI interface.

7.5 Circuit boards

Two circuit boards are designed to serve as the finished prototype. The main circuit board contains all the sub-modules except the power amplifier which is has a separate board to simplify the matching procedure. Although the main circuit board is made quite small, there should still be enough space to add the power amplifier to a board of the same size. The main circuit board is shown in figure 21.

Figure 21: Main AIS MOB circuit board

8 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.

8.1 Reception of messages

Figure 22 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 is as expected. This data can also be compared to the signal broadcasted by a ship shown in figure 6, 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.

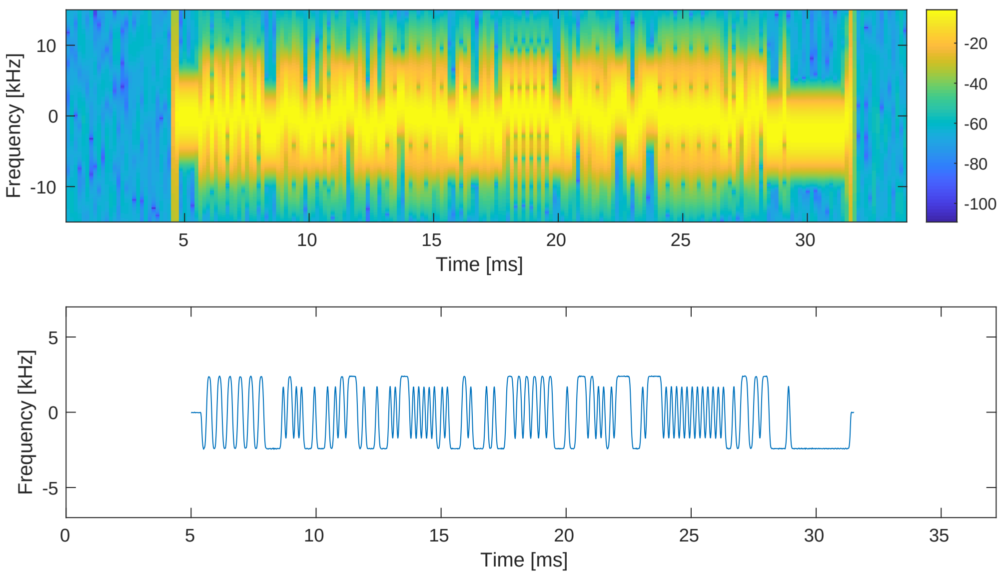

Figure 22: Spectrogram of message sent by the system

Although the data from figure 22 could be used to verify the correctness of the transmitted data, a simpler and better way is to use standard AIS equipment. A simple AIS receiver from XX, is used together with the OpenCPN software in order to receive messages from the system. Figure XX shows the reception of a distress message.

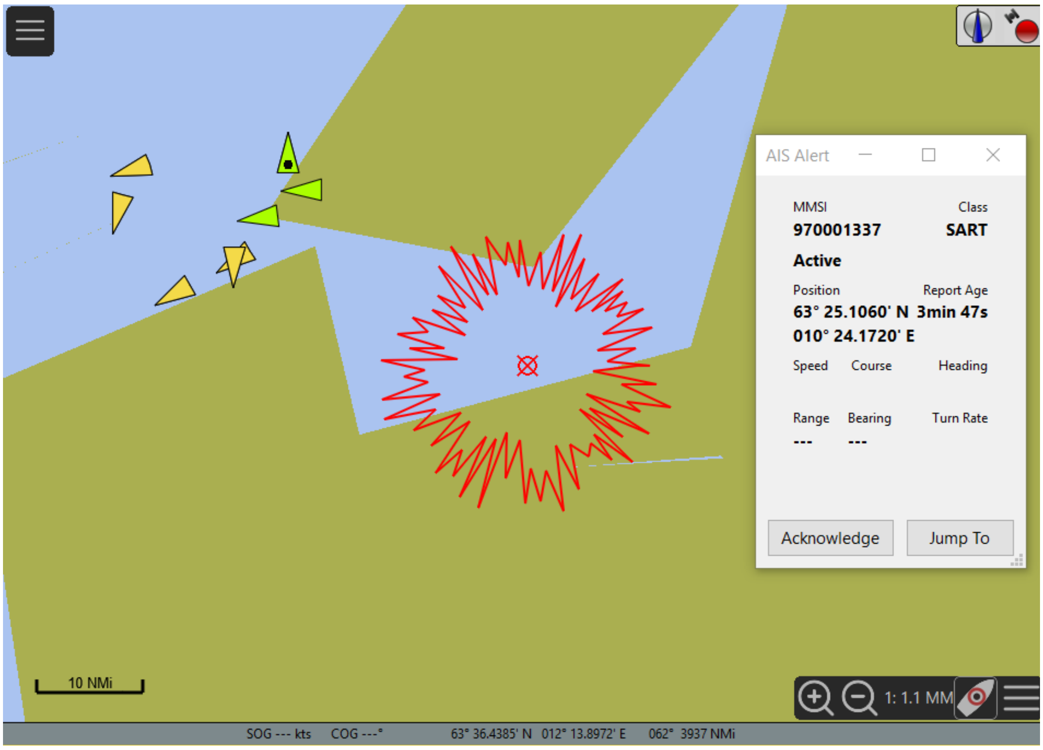

Figure 23: Reception of distress message in OpenCPN

8.2 Power consumption

The power consumption is measured with a source measurement unit (SMU) from Qoitech. The manufacturer of the SMU states an accuracy of $\pm(1\% + 0.5\mu\text{A})$ [25]. 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 24 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.

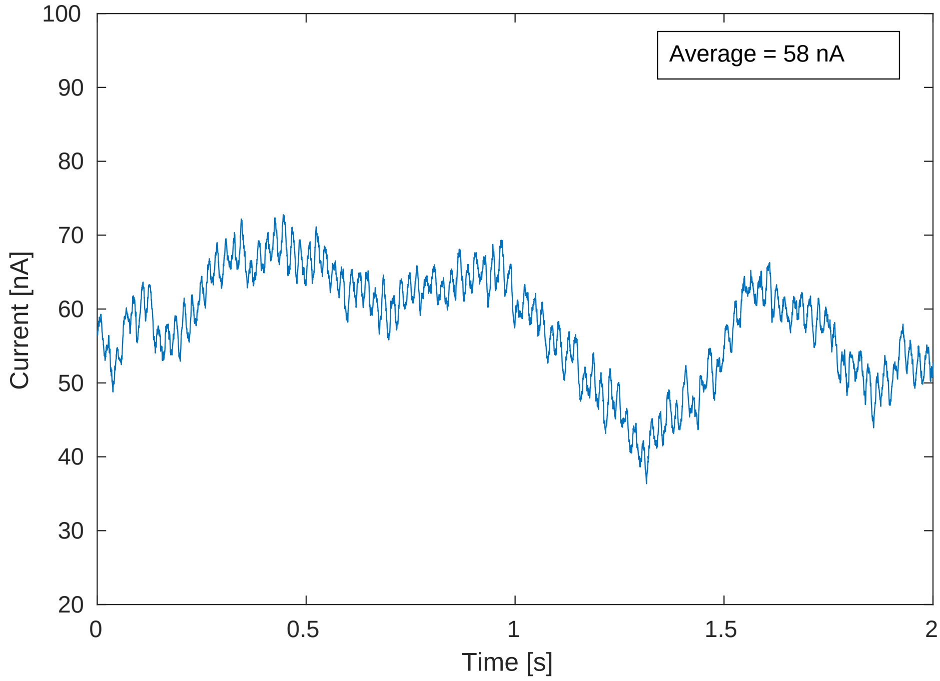

Figure 24: Power consumption wile inactive

Figure 25 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.

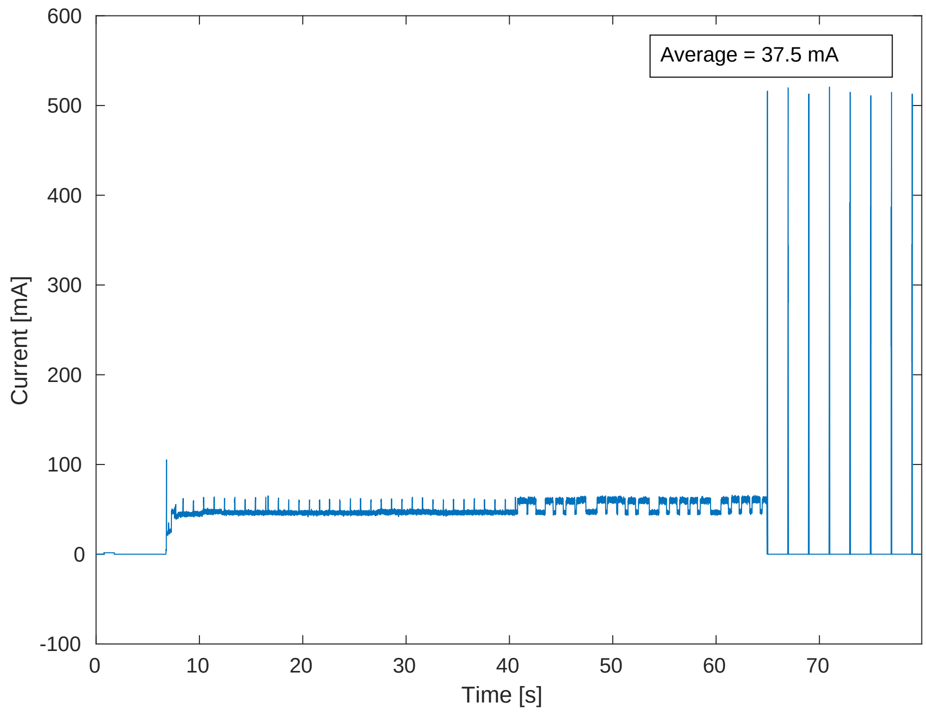

Figure 25: Power consumption at startup

Figure 26 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 the GPS acquisition represents about 84 % of the average current draw here. The average current draw for the data in figure 26 case is 11 mA. The average time for the GPS reacquisitions is 13 s.

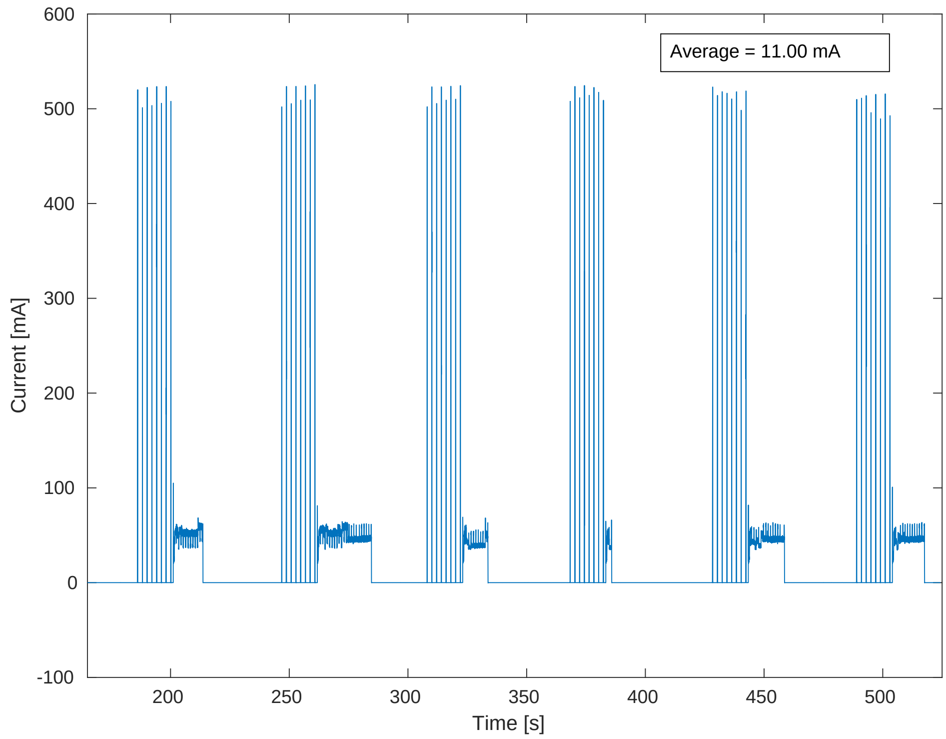

Figure 26: Power consumption while active

Figure 27 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.

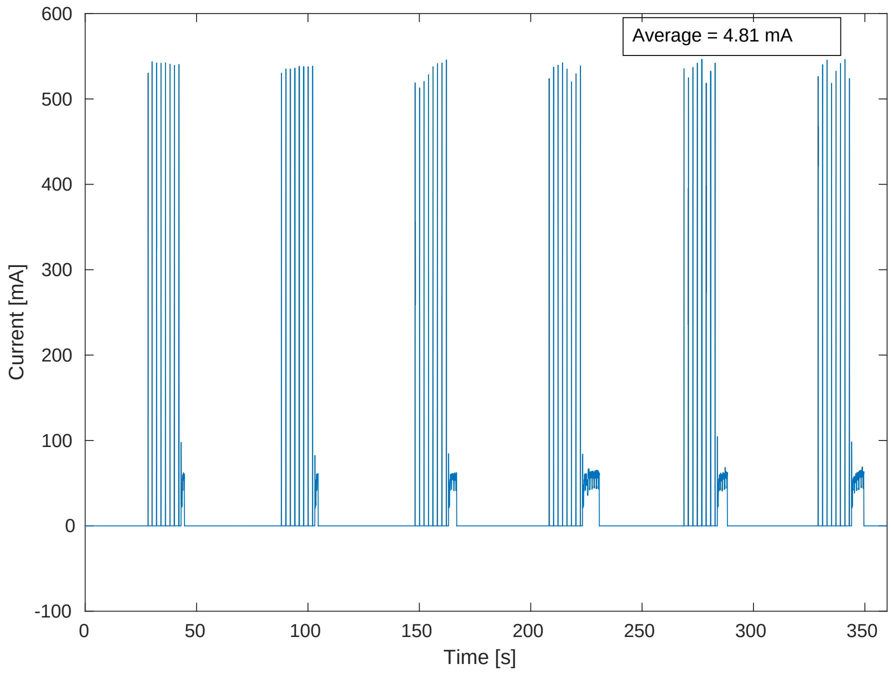

Figure 27: Power consumption while active in good conditions

In addition to measure the consumption during different times of operation, the system is set up for a long duration test in order to check the available operation time of the system. For this, a script is written to log incoming messages from the AIS receiver. In order to avoid other AIS equipment receiving these messages, the system was configured to send on a channel at 161.7 MHz, an the distress message was exchanged for a standard position report of equal length. In total this setup received XXX messages, and the system was found to operate for XX hours.

8.3 Output spectrum and power

The output spectrum of the system is measured with a spectrum analyser from Rohde & Schwarz. Figure 28 shows this measurement for channel 1, and figure 29 for channel 2. The output reaches 29 dBm.

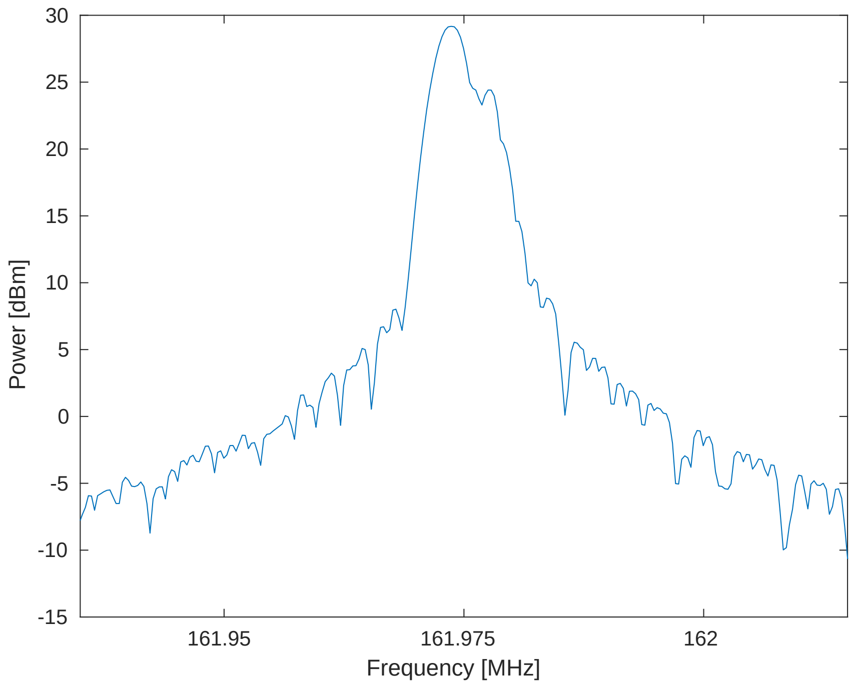

Figure 28: Output spectrum channel 1

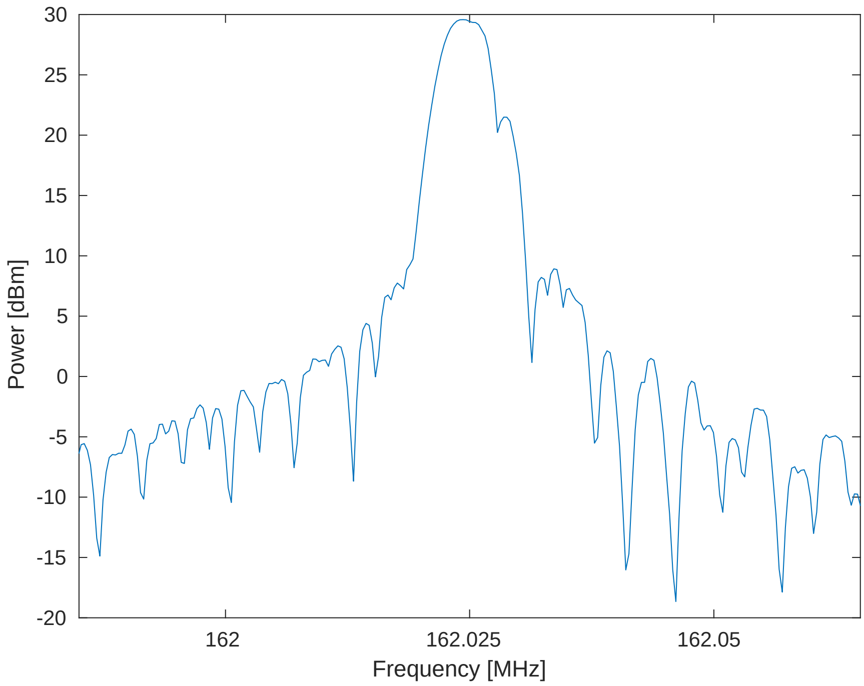

Figure 29: Output spectrum channel 2

9 Discussion

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 over board. The measured current draw of the system while inactive, was measured to 58 nA, and estimated to be 20 nA. The measured value has a large uncertainty due to the accuracy of the measurement device, but the calculated worst case value of 559 nA would still only result in 49 mA h during the course of 10 years. The limiting factor of the lifetime while the system is inactive can therefore be said to be the shelf life of the battery.

10 Conclusion

11 Acknowledgements

References

[1] PANBO, Ben Ellison, Testing AIS MOB beacons, ACR's DSC feature especially, 08 2017.

[2] European Telecommunications Standards Institute, Maritime low power personal locating devices employing AIS; Harmonised Standard covering the essential requirements of article 3.2 of the Directive 2014/53/EU, 02 2016. ETSI EN 303 098, V2.1.0.

[3] CML Microcircuits, CMX7045 AIS SART processor product preview, 11 2011.

[4] P. Havinga and G. Smit, "Design techniques for low-power systems," Journal of systems architecture, vol. 46, no. 1, pp. 1–21, 2000.

[5] D. Li, P. H. Chou, and N. Bagherzadeh, "Mode selection and mode-dependency modeling for power-aware embedded systems," in Proceedings of the 2002 Asia and South Pacific Design Automation Conference, ASP-DAC '02, (Washington, DC, USA), pp. 697–, IEEE Computer Society, 2002.

[6] Silicon Labs, Energy Optimization, 11 2013. AN0027.

[7] Nordic Semiconductor, nRF52840 Objective Product Specification, 12 2016. v0.5.

[8] J. R. Barry, E. A. LEE, and D. G. Messerschmitt, Digital Communication, vol. 1, pp. 249–251. Springer Science+Business Media, LLC, 3 ed., 2004.

[9] T. S. Rappaport, Wireless Communications, pp. 318–319. Prentice Hall PTR, 2 ed., 2015.

[10] International Telecommunication Union, Technical characteristics for an automatic identification system using time division multiple access in the VHF maritime mobile frequency band, 02 2014. ITU-R M.1371-5.

[11] Ocean Signal, The worlds smallest personal locating AIS Man OverBoard device with integrated DSC. Available: http://oceansignal.com/products/mob1.

[12] Y. Li, K. L. Chung, S. Xie, Y. Yang, M. Wang, and X. Geng, "An improved design of automatic-identification-system-based man overboard device: A multidisciplinary product," IEEE Access, vol. 6, pp. 25220–25229, 2018.

[13] Ocean Signal, LB9M battery pack for MOB1, datasheet. Available: http://oceansignal.com/wordpress/wp-content/uploads/LB9M-PSDS.pdf.

[14] Energizer, Energizer 123, product datasheet. EL123AP.

[15] Ocean Signal, rescueME MOB1, User manual, 2018.

[16] Kannad, SafeLink R10, AIS survivor recovery system, 2011.

[17] CML Microcircuits, CMX7045 AIS SART processor datasheet, 02 2013.

[18] Silicon Labs, AN888: EZR32 Quick Start Guide. Table 1.1.

[19] Silicon Labs, EZR32HG Wireless MCUs EZR32HG220 Data Sheet.

[20] Quectel, L80 Hardware Design, 08 2013.

[21] Varta, CR 123 A Lithium Manganese Dioxide Datasheet, 09 2014.

[22] Silicon Labs, Si4X6X AND EZR32 HIGH-POWER PA MATCHING, 2016. AN648.

[23] NXP, AFT05MS003N RF Power LDMOS Transistor, 08 2015.

[24] Fondriest Environmental, Inc, Conductivity, Salinity and Total Dissolved Solids., 03 2014.

[25] QOITECH, TECHNICAL SPECIFICATION, OPTIMIZE POWER USAGE IN IoT DEVICES, 2017. Otii/TS_20180821_v1.

A AIS messages 1 and 14 content

A.1 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**	

A.2 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**	