Low-Power Microcontroller-based Acoustic Modem for Underwater Robot Communication

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Abstract

This paper presents a low-power microcontroller-based acoustic modem for low-range communication based on aspects of whale and dolphin communication. The approach is to decrease influences by using a frequency shift keying (FSK) modulation combined with frequency hopping spread spectrum (FHSS). Addressing individual recipients (unicast) as well as a group (multicast) or all recipients (broadcast) is done by spreading the outgoing signal by orthogonal signatures. Using these signatures means an overhead of the transmitted data but increases the interference resistance and the reliability of the communication.

1 Introduction

Underwater communication is still a difficult and challenging task. An application example of a underwater communication systems are small autonomous underwater vehicles (AUV) [2, 1]. One task of these small robots is e.g. the environmental monitoring of rivers and lakes. They shall cooperate in a swarm and need to communicate with each other to improve the quality and coverage of measured data. Thereby often only short ranges are sufficient. The requirements for this field of application are mainly small form factor and low energy consumption.

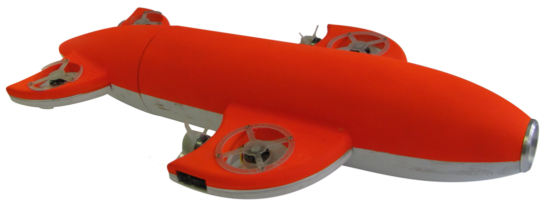


Figure 1: The small AUV MONSUNII with a lenght of 60 cm, diameter of the hull of 10 cm and a weight beneath 3 kg

Figure 1 shows the second generation of our small AUV MONSUN (MONitoring System and Underwater Navigation Robot) [3]. With a length of about 60 cm, the diameter of the hull of 10 cm and a weight beneath 3 kg. Therefore not only the size of the modem has to be small but also the size of the transmitter and receiver.

There are three common technologies for underwater communication: radio, light and sound. Unfortunately, electromagnetic (EM) waves such as Wireless LAN or Bluetooth perform in the medium water not comparable to radio communication in the medium air. This is due to the conducting nature of water, particularly in case of salt water. Whereas the absorptive loss in freshwater is independent of the used frequency, the absorption in saltwater is depending on the frequency. The higher the used frequency is, the more the range decreases. But using low frequencies implies requirement of large antenna sizes. Thus, using EM waves for underwater communication in sensor networks or between underwater robots is still a challenge [4, 5].

Using optical waves for underwater communication would have an advantage in the high data rates up to 1 Gbps on the one side [6]. But on the other side there are several disadvantages using this technology: first, the ambient light near the water surface can affect the communication. On the other hand, optical signals are rapidly absorbed with increase in water depths. Finally the main disadvantage is the optical scattering caused by floating particles. Therefore optical communication is only suitable for very short ranges.

The most frequently applied technique for underwater communication is the use of acoustic waves, because of their relatively low absorption. As in the case with the EM waves, higher frequencies are more absorbed than lower ones, though the salinity has hardly an effect on this. The propagation speed depends on the temperature (circa 1500 m/s at 25° C) and is very slow in comparison with EM or light waves. Dolphins e.g. use a frequency range of 200 Hz up to 24 kHz for communication [7].

But echoes and reflections represent a large problem of underwater communication with acoustic waves. Dolphins and whales, which use sound for communication, have adapted to the situation quite well by changing the frequency of their singing across a broad bandwidth. This allows avoiding interferences like echoes, reflections and noise like marine engines.

This paper presents a low-power microcontroller-based acoustic modem based on aspects of whale and dolphin communication. Influences are decreased by applying the frequency hopping spread spectrum (FHSS). This improves the data rate since it does not need to wait for the channel clearing to send the next symbol on another frequency. In order to improve the interference resistance and to allow unicast, multicast and broadcast, the signal is additionally spread by orthogonal codes.

This remainder of this paper is organized as follows. In Section 2 related work is discussed while we describe our design rationale of our acoustic modem in Section 3. In Section 4 we introduce the relevant hardware parts and present the principal algorithm of the frequency analysis and the implementation in Section 5. Experiments are shown in Section 6 and we conclude with a summary in Section 7.

2 Related Work

Acoustic underwater communication has been investigated by several researchers and companies but most of them are designed for long range communication. Leading companies in the field of acoustic underwater communication are LinkQuest [8] and DSPComm [9]. While DSPComm is using the direct-sequence spread spectrum (DSSS) modulation for the transmission of the data, LinkQuest uses its own devising acoustic "Broadband Spread Spectrum Technology". As a controller both modems use a digital signal processor (DSP). The communication range of the LinkQuest modem is up to 6000 m with a data rate of up to 9600 bits/second, while the AquaComm modem can achieve a range of 3000 m at a data rate of 100-480 bits/second. A disadvantage of both modems is their size and weight especially in case of the LinkQuest modem with a weight of 4.1 kg (in water) and a length of 286 mm and a diameter of 144 mm.

Evologics [10], a spin-off of the Technical University Berlin, developed an acoustic underwater modem based on the physics of biocommunication in dolphins by implementing their Sweep-Spread Carrier (S2C) technology. By using horizontal underwater (multi-path) channels, up to 6.5 kbit/second at a range of 8000 meters can be achieved. One application of this modem is an early warning system for tsunamis in front of Indonesia.

A compact and low-power acoustic modem was developed by Freitag, et al [11]. This modem is constructed in a modular way and can be extended as required. It applies low-rate frequency-hopping frequency-shift keying (FH-FSK) for low-power mode and high-power variable rate phase-coherent keying (PSK). A Texas Instruments fixedpoint digital signal processor (DSP) providing up to 160 MIPS is uses as processor as well as a floating point coprocessor to execute the PSK equalization algorithm.

A small microcontroller based acoustic modem is presented in [12]. The main goal of this approach is to design a small and inexpensive low-power underwater modem for short-range communication. Therefore they implemented a wake-up receiver that wakes up when receiving a frequency of 18 kHz. Data transmission is done by binary frequency shift keying (BFSK) that means that only two frequencies are used. This technique is more interference-prone than techniques like DSSS or FHSS since noise in a used frequency can interfere with the whole transmission.

3 Design Rationale

The main goal of the design is to build a small, robust and low-power underwater modem for communication within a swarm of AUVs. Thereby we focus on short-range communication concerning the small size of the AUVs and the area the swarm will cover during its mission on the one hand and the possibility to establish long-range communication by multihop routing over several AUVs on the other hand. The target range of our modem amounts to 50-200 m.

Our design applies several techniques that are inspired by the nature. Whereas the range of EM waves decreases by increasing the frequency and optical waves are influenced by for example floating particles, acoustic waves can propagate the more the density of the medium increases. Dolphins and whales use acoustic waves and are able to communicate with each other over a range of several kilometers. High propagation has nevertheless a disadvantage: it can cause reflections, superimpositions and effacements of the waves. This may result in gaps in signals and messages. To counteract this dolphins change the frequency of their singing across a broad bandwidth continuously. We apply this technique by not using the same frequency consistently like it is down by the normal FSK modulation but vary the used frequencies as well. Therefore we employ the frequency hopping spread spectrum modulation and change the frequency every bit.

To address a communication partner dolphins use so-called signature whistle [13]. This whistle appears to serve as an individual identification, much like a name. Bottlenose dolphin calves for example develop their signature whistle that is patterned on the signature whistle of the parents during their first year of life. All other dolphins in a group learn the signature of each other and can address a special member of the group by whistling the signature of the communication partner. We use signatures as well for addressing the communication partner but not as a special melody but as a code for coding and encoding of the message. Each modem has its own signature and the signatures of all other modems in its memory. If a message shall be sent from modem A to modem B, the message is spread by the signature of modem B by an xor-operation of each data bit and the signature. To decode the message the recipient has to perform an exclusive disjunction of the received message with its own signature and to integrate over the length of the signature. An example of coding and encoding a message by two different recipients is given in Table 3. It can be seen that receiver C cannot decode the message to receivers B with its signature.

Table 1: Signature based coding and encoding of a message received from two different recipients.

Coding Transmitter A		
Data from A to B	1	0
Signature of B	11001100	11001100
Result of xor-operation	00110011	11001100
Decoding Receiver B		
Received Data	00110011	11001100
Signature of Receiver B	11001100	11001100
Result of xor-operation	11111111	00000000
Decoding Receiver C		
Received Data	00110011	11001100
Signature of Receiver C	10101010	10101010
Result of xor-operation	10011001	01100110

Since all signatures are orthogonal to each other, the hamming distance of the signatures is maximal. If the hamming distance of a code is h up to $(h-1)$ errors can be detected. To correct an error the hamming distance has to be larger than $2r+1$ where r is the quantity of error correctable bits [14]. For our modem we use signatures with a length of eight and hamming distance of four that allows to detect up to two, and to correct one error. On the one hand this means a certain overhead of the data to be sent but but on the other hand the transmission becomes more reliable. Even if one frequency is noisy it has no influence on the recipient since this error can be corrected by the code.
The signatures are used as well for broadcast and multicast by using one signature for all (broadcast) and a set of signatures for different groups (multicast).

4 Hardware assembly

The modem is divided into two parts: the transmit and the receive unit (Figure 2).

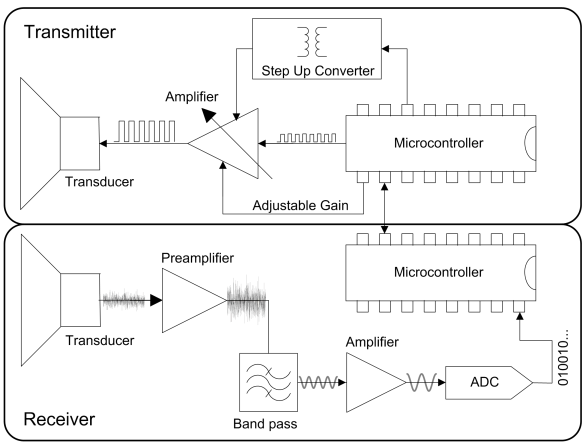


Figure 2: Block diagram of the transmitter and receiver.

These units are operating independently of each other, so the sender can still send messages even if the receiver has broken down and the receiver can still receive commands although the transmitter can not reply. Nevertheless they are connected by a signal line so that the transmitter is informed by the receiver while receiving a message and vice versa. Both, the sender and the receiver are controlled by a microcontroller and are described below in more detail.

4.1 Transducer

For the first tests transducers were built from inexpensive piezoelectric loudspeakers and fitted into a plastic housing. Experiments have shown that the frequency response of the piezoelectric discs is not as linear as anticipated but has a high resonant frequency at 23 kHz. These transducers will be replaced by new transducers build of piezoelectric tubes in the near future.

4.2 Transmitter

The main task of the transmitter is to receive data from an external source and to modulate a signal based on this data that is then sent by the transducer. The communication between the external source, e.g. a PC or a controller, and the transmitter is performed over a standard serial port with a baudrate of 57600 and $8N1$ mode. An ATmega48 was chosen as controller for the transmitter because of its small size and low power consumption. The signal generation is done by the pulse-width modulation (PWM) generation of the ATmega. To equal the ON- and OFF times of the PWM signal results in a rectangular signal with

$$f_{PWM} = \frac{1}{t_{ON} + t_{OFF}} Hz.$$

The output of the PWM generation is amplified by a small low voltage audio power amplifier (LM386N-1). This amplifier is supplied by a step-up converter that increases the supply voltage of the modem from 5 V to 12 V and as a result the output voltage to 10 V_{pp} which conforms an output power of 750 mW. To keep the power consumption as low as possible the step-up converter and the amplifier are switched on by the microcontroller only if there is a signal has to be sent. Because the outgoing signal from the transducer is non linear (see Section 4.1) the amplification of each frequency is controlled by the microcontroller by a serial peripheral interface (SPI)-controlled digital resistor that allows a very fine granular regulation.

4.3 Receiver

On the receiver side the incoming signal is firstly boosted by a preamplifier that allows an amplification up to a factor of 720 and has a very high input impedance to stress the transducer as low as possible. Behind the preamplifier a bandpass filter is arranged. This bandpass consists of a low pass filter and a high pass filter both implemented as an active eight-order filter. Since the lowest frequency of 15 kHz should pass the low pass nearly unmuted the cutoff frequency of the low pass filter was set to 13 kHz. That results in a decay of 0.47 dB at 15 kHz. Similarly the cut-off frequency of the high pass filter was set to 33 kHz in order to achieve a least possible decay at the highest used frequency of 30 kHz. A second amplifier is located behind the bandpass to boost the filtered signal again and to adjust the voltage for the following analog to digital converter (ADC). The used ADC of type $ADC102S101$ is applicable for conversions up to 1 Msps and has a resolution of 10 bit. The ADC is connected to the microcontroller via the SPI bus and is clocked at the highest possible speed of the microcontroller. As controller for the receiver an ATmega168 was chosen. The microcontroller has 16 Kb program memory (ROM), 1 Kb of data memory (RAM) and a clock rate of 20 Mhz.

5 Software Implementation

This section describes the software implementation of the transmitter and receiver.

5.1 Transmitter

The incoming data from the serial interface is stored in a ring buffer since acoustic sending needs more time than receiving of the data from the serial port. After the transmitter received the name of the recipient the related signature is loaded from memory and is used to spread the transmission data. Based on a predefined hopping-sequence, the frequencies are generated by the internal PWM generator of the ATmega by loading the corresponding periods in the timer registers.
To synchronize the transmitter and receiver the transmitter sends a predefined preamble ahead of the payload composed of the two frequencies 18 kHz and 25 kHz that are sent alternating.

5.2 Receiver

Because of the low computing power of the microcontroller, the frequency analysis can not be performed by the fast Fourier transform (FFT)-algorithm. Since only a few spectral components have to be computed, the Goertzel-Algorithm [15], which is normally used for the recognition of dual-tone multi-frequency signaling (DTMF) tones produced by the buttons pushed on a telephone keypad, was implemented. This algorithm is more efficient than the FFT, if less than $5/6 \cdot \log_2 N$ spectral components have to be computed. In contrast to the FFT, N does not need to be an integral power of 2.
For each frequency that will be used for data transmission, a coefficient has to be computed in advance. The coefficient is computed as

$$coeff(f_n) = 2 \cdot \cos\left(\frac{2\pi}{N} \cdot \left(0.5 \cdot + \frac{N \cdot f_n}{f_{sample}}\right)\right),$$

where N is the number of samples and f_{sample} the sampling rate. The number N of samples is calculated by the formula

$$N = \frac{f_{sample}}{\Delta f},$$

where Δf is the frequency distance of the regarded frequencies. Since this coefficient will not change it can be stored in the ROM of the microcontroller.
Before receiving the payload, the receiver has to synchronize itself with the clock of the transmitter. As described in section 5.1 the transmitter sends a preassigned preamble. This preamble is detected by the Sliding Goertzel algorithm [16, 17] that is shown in Figure 3.

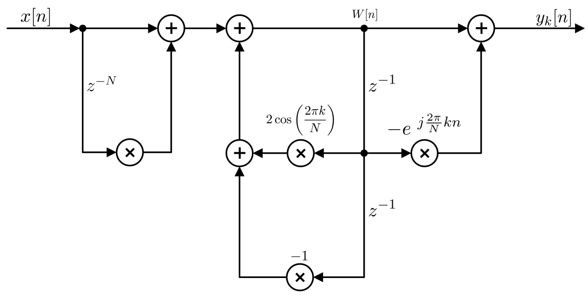


Figure 3: Structure of the Sliding Goertzel filter that is used for the synchronization of the transmitter and receiver. The computation of the feed forward path must be performed for each input sample.

This algorithm allows the evaluation of the signal strength of an incoming signal in a sliding window at each time step and can be implemented like shown in Listing 1.

Listing 1: Sliding Goertzel Algorithm

```
f_n = preamble frequency;
Q_0(f_n) = coeff(f_n)·Q_1(f_n) − Q_2(f_n)+x_n −x(n−N);
Q_2(f_n) = Q_1(f_n);
Q_1(f_n) = Q_0(f_n);

Magn(f_n)=Q_1(f_n)^2+Q_2(f_n)^2 −Q_1(f_n)·Q_2(f_n)·coeff(f_n);
```

This algorithm needs one multiplication and three additions for the backward path and five multiplications and two additions for the forwards path.
If the magnitude of the evaluated frequency exceeds a predefined threshold the global maximum of the magnitude for this frequency is determined within the given transmission time of the frequency. If this peak is evaluated, the peak of the next frequency of the preamble is determined. After detecting all peaks of the applied frequencies in the preamble the average value of these points is computed.
If the synchronization is complete, the payload can be received. Instead of using the Sliding Goertzel algorithm furthermore, the faster standard Goertzel algorithm (Figure 4) is applied. The advantage of this algorithm compared with the Sliding Goertzel algorithm is that the forward path in Figure 4 has to be computed only once after the arrival of the Nth input sample. This reduces the number of arithmetic operations to only one multiplication and two addi-

tions in case of the backward path and five multiplications and three additions in case of the forward path. And example of an implementation of the Goertzel algorithm is given in Listing 2.

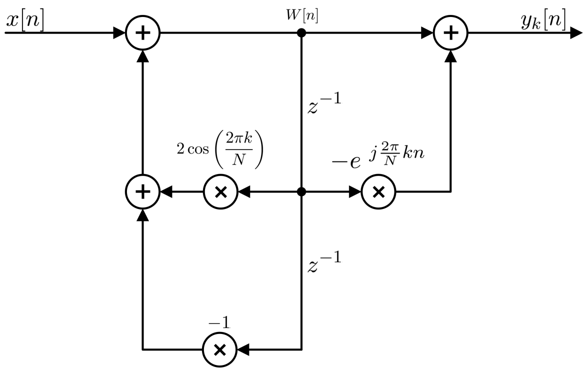


Figure 4: The second order Goertzel IIR Filter. Since the forward path has to be computed once after the arrival of the Nth input sample, the algorithm needs only $N+2$ real multiplies and $2N+1$ real adds to compute a N-point DFT.

Listing 2: Goertzel Algorithm

```
for i = 1 to N
  foreach frequency f_n to evaluate
    Q_0(f_n) = coeff(f_n)·Q_1(f_n) − Q_2(f_n)+x_n;
    Q_2(f_n) = Q_1(f_n);
    Q_1(f_n) = Q_0(f_n);
  end foreach
end for

foreach frequency f_n to observe
  Magn(f_n)=Q_1(f_n)^2+Q_2(f_n)^2−Q_1(f_n)·Q_2(f_n)·coeff(f_n);
end foreach
```

After the complete reception, the incoming data will be despread by using the own spread code as well as the spread code for multicast or broadcast.

6 Experimental Results

In the following sections, we first describe our experimental flow and then our results.

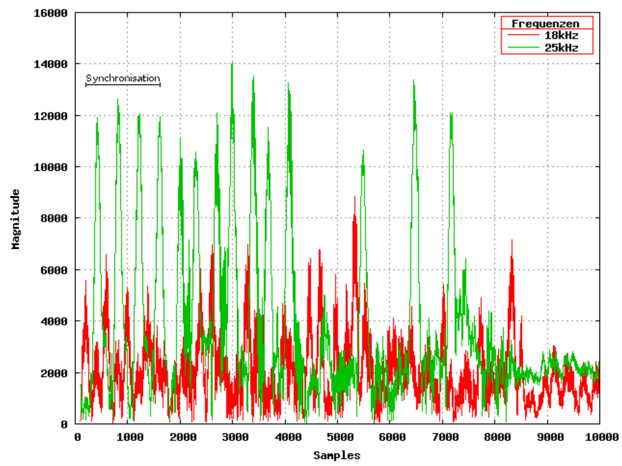
6.1 Experimental Setup

The experiments were performed in a pool. This represents an difficult environment because of the increasing occurrence of reflections and echoes. A reliable communication should be established in this environment since we use this pool for experiments with MONSUN. An immediate evaluation of measurement data of MONSUN would help to improve the algorithms and their parameters.
Transmitter and receiver were placed in different distances and orientations to each other since the angle of acoustic wave propagations is not equal in all directions due to the used transducers.

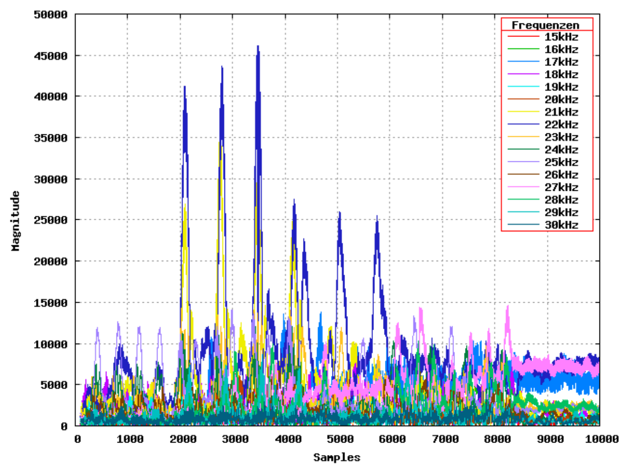
Messages with different payload and length were sent in order to evaluate the robustness of the applied algorithm and to examine the accuracy of the synchronization over the transmission.

6.2 Experimental Results

In Figure 5 results from an experimental setup can be seen. Figure 5(a) shows two extracted frequencies from an incoming signal that are used as the preamble. As it can be seen, the peaks of the frequency are easy to detect. Furthermore, there are small peaks behind the original signal, which are caused by reflections in the test pool.



(a) This Figure shows the two frequencies that are used for the synchronization. As it can be seen peaks are followed by small pikes that are caused by reflections.



(b) This plot shows a result of the frequency analysis for all used frequencies. the different magnitudes of the frequencies are caused by the nonlinearity of the transducers.

Figure 5: A cutout from an experimental result.

Figure 5(b) shows the results of the frequency analysis for all used frequencies. It can be seen that the signal strength of the different frequencies are not similar, which is caused by the natural frequency of the used piezoelectric loud-

speakers. Even the implemented adjustment of the amplification (see Section 4.2) could not compensate this completely. It became apparent that the used transducers are unsuitable for this application. The signal is not radiated equally and the quality of the reception depends strongly on the orientation of the receiver to the transmitter and the used frequencies. Nevertheless the transmitted data was received successfully.
It has been shown that the used algorithms prevent the influences of echoes, reflections and noise and can correct errors in case of noisy frequencies.

7 Conclusion

As result of the experiments it was shown that the presented acoustic modem is suitable for small underwater robots or sensor nodes, if a small and low power solution is required. Based on the frequency hopping and the redundancy of the transmitted data by the used spread codes, the impact of echoes, reflections and noise can be decreased. The maximum range of the modem of 50m is currently limited by the quality of the used transducer. Using the new transducers would expand this range. The bandwidth of the modem is limited by the Goertzel algorithm. Using the frequency spectrum described in this paper, a bandwidth of 1000 bits/second can be achieved. By increasing the interval between the used frequencies, higher bandwidths would be possible.
A next step will be the integration of the modem in the AUV MONSUN [3] to enable the communication and collaboration between the swarm members. This allows e.g. to determine a failure of a swarm member by its neighbors or the exchange of the position and health status of the AUVs.

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