# Robust, Digital Communication in the Horizontal Underwater Channel

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## Introduction

Digital communication trough air typically utilizes electromagnetic waves (radio). State-of-the-art digital signal processing methods enable robust radio transmission over long distances.

Underwater communication with electromagnetic waves is not possible at longer distances. Therefore, transmission by sound is used. However, the transmission channel is highly variable and affects the range of the system. Different water temperatures, the salinity of the water and the water depth are important factors that influence the sound velocity. Different sound velocities resulting in layers in the water at which the sound waves break. Reflections on the surface, the sea floor and other objects under water cause reverberation. Frequency fading, Doppler shifting and different noise types are additional factors that influence the transmission. This is the reason why digital transmission methods under water are always to be assessed with regard to robustness.

This paper presents an improved form of the "Multiple Frequency-Shift Keying" (MFSK) method. With the help of different configuration sets, an adaptation to the variable characteristics of the underwater sound channel is done. Depending on the current environmental conditions, a trade-off between robustness and data rate must always be complied with. The results from simulations of different sea areas are presented.

## Scenarios and Applications

New opportunities in the area of underwater sensor technology increase the necessity for robust digital communication under water.
Beside the civilian scope, military applications demand for robust digital underwater communication.

Imaginable civilian applications are remote control in offshore oil industry, pollution monitoring in environmental systems, collection of scientific data recorded at ocean-bottom stations, speech transmission between divers and mapping of the ocean floor for detection of objects as well as for the discovery of new sources.

For military purposes, digital underwater communication becomes more and more a key technology for affiliated operation of submarines with surface vessels and for the communication with unmanned or autonomous underwater vehicles (UUVs, AUVs). These different platforms and applications and the complexity of the underwater channel itself postulate different requirements for the communication link.

Getting the possibility to communicate between each other enlarges the range of information exchange and improves the basis of decisions within an operational scenario.

## The hydroacoustic channel

To provide a robust digital communication in the underwater sound channel it is mandatory to be aware of the relevant channel effects that affect the transmission. From a system-theoretical perspective the underwater channel could be described as follows:

$$y(t) = \int_{-\infty}^{\infty} h(\tau,t)\cdot x(t-\tau)\mathrm{d}\tau + n(t) \qquad (1)$$

The output signal $y(t)$ is derived as the convolution of the impulse response $h(\tau,t)$ and the input signal $x(t)$, added with a noise term $n(t)$. Where $\tau$ is the delay and $t$ represents the time vector. It should be pointed out that the impulse response is time variant. This leads to certain effects that are relevant for the digital underwater communication:

**1. Spectral fading:** Different sound paths with different run-times could lead to destructive overlay of sound in certain frequencies. This results in a reduction of sound energy in certain frequency bands.

**2. Doppler spread / Doppler shift:** Due to different relative motion between different reflecting points and the transmitter under water, a Doppler spread and a Doppler shift can be introduced. The Doppler spread leads to a frequency spread, a widening of the carrier frequencies of the digital transmission. The Doppler shift changes its frequency. These effects can lead to inter carrier interference (ICI).

**3. Time spread:** Due to reflections on different objects under water, the seafloor, the sea surface, particles in the water or different layers in the water column, a time spread can be introduced. This may result in a crosstalk between symbols of the digital transmission, known as inter symbol interference (ISI).

In Figure 1 (top) an example of a recorded impulse response train is shown. In total 250 impulse responses were recorded, indicated on the ordinate of the figure. On the abscissa, the time delay is shown. In this example, the variance of the impulse response of the underwater channel is visible. The characteristics of the channel lead to a Doppler spread, that is visible in the delay Doppler spread plot in Figure 1 (bottom).

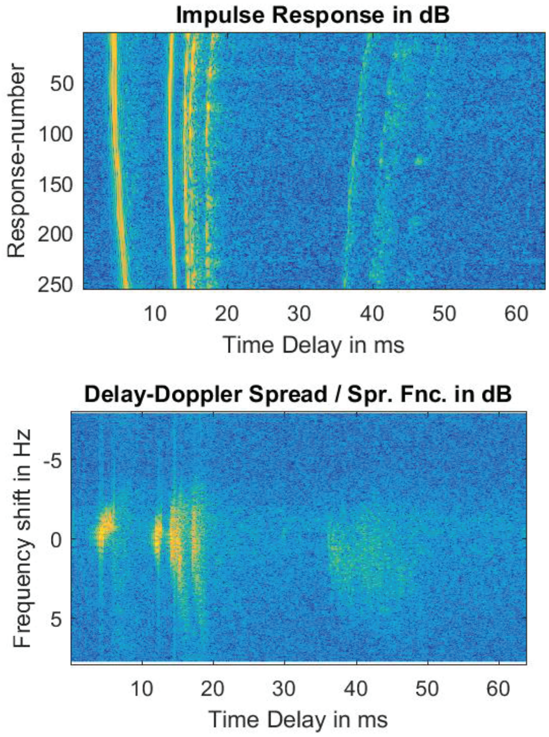


**Figure 1:** Example of a time variant impulse response (top) and the corresponding delay-Doppler spread (bottom).

In Figure 2 another impulse response is shown. The time variance of the channel is not as high as the impulse response shown in Figure 1. Nevertheless, the amount of spectral fading can be critical for the digital transmission. Figure 2 (bottom) indicates this problem. Here the power spectral density (PSD) in baseband is shown for a transmission with a bandwidth of 4 kHz. Several frequency areas suffer from spectral damping up of -20 dB to -30 dB.

## Multi Frequency Shift Keying (MFSK)

Different physical layer methods are imaginable to transmit information through water. They are all well know from radio or mobile communication. Due to the complexity of the underwater channel and variety of application needs there is not only one physical layer method that fits for all. Different methods and several configurations of them are necessary to serve the respective requirements.

Multi Frequency Shift Keying (MFSK) is one possible incoherent method as a variation of Frequency Shift Keying (FSK). It does not use only two frequencies but an alphabet of M orthogonal tones over a given bandwidth.

To overcome the complex channel effects and to increase the robustness MFSK is combined with other techniques mostly at the expense of data rate.

Figure 3 illustrates the block diagram of the MFSK transmitter which ELAC Nautik uses for its underwater telephone.

At first, the information bits to be transmitted will be scrambled to provide an equal distribution of zeros and ones to optimize the crest factor of the signal.

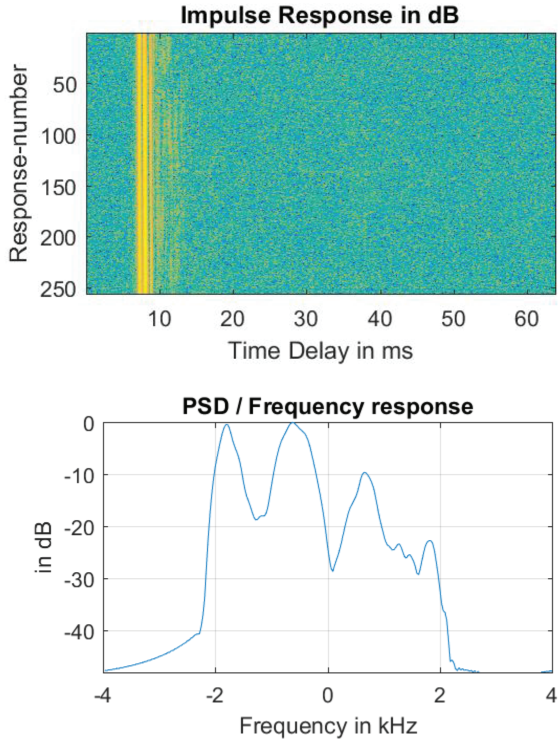


**Figure 2:** Example of a time variant impulse response (top) and the corresponding power spectral density in baseband (bottom).

In the next step the scrambled information bit stream will pass through a forward error correction encoder to insert redundancy in time domain. A convolutional encoder with rate ½ or ¼ and memory length of three is used.

To ensure best performance and correction capability of the encoder a block interleaver is used after the encoder, which changes the order of the coded bit stream.

Fading or short term error would typically lead to block errors which would decrease the performance of the decoder drastically. With the interleaver, block errors of the channel will be dissolved in bit errors within the received coded data stream, which can be handled by the decoder.

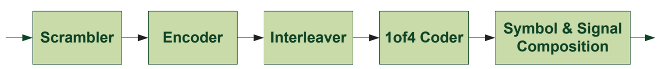


**Figure 3:** Block diagram of the MFSK transmitter

Redundancy in the frequency domain will be inserted by use of 1of4 coding in combination with a Gray code bit mapping.

Two coded bits will be represented by one 1of4 group in frequency domain. The mapping considers a Gray code. This ensures that in case of a one frequency bin shift error (for example due to Doppler spread or fading effects) only one bit error will occur after demodulation and demapping.

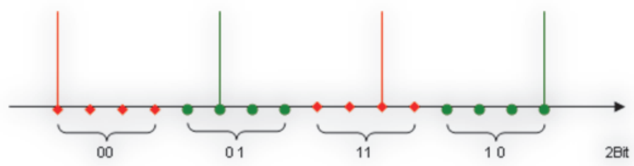


**Figure 4:** Bit mapping as 1of4 groups with Gray code within a MFSK symbol

Thus, the spectral information density will decrease by the factor two.

To address broader fading effects 1of4-2 can be chosen. With this method transmission of same bits in the upper and lower sideband simultaneously and an additional data rate reduction of factor 2 are done.

The symbol and signal composition is necessary for the modulation of the multicarrier symbols with a certain symbol duration. It composites all symbols to one MFSK burst under optional consideration of guard times.

Varying the symbol length and the inclusion of guard times between the symbols address the inter symbol interference (ISI) problem on channels with a large time spread.

Extending the symbol length increases the signal to noise ratio, enlarges the FFT resolution and weakens the ISI effect for a given channel time spread.

Introducing guard times between the symbols enables the fading of echoes and can avoid ISI completely if the guard time is chosen big enough.

Thus the combination of both techniques can improve the quality of the data link with the disadvantage of reduced data rate.

**Table 1:** MFSK configuration and data rates, increasing in robustness.

| Num-ber | Symbol Length factor | Gap factor | Fre-quency coding | FEC Rate | Bytes per burst | Data rate [bits/s] (LF) |
|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 1-of-4 | ½ | 479 | 766 |
| 2 | 1 | 0 | 1-of-4-2 | ½ | 239 | 382 |
| 3 | 2 | 0 | 1-of-4-2 | ½ | 119 | 190 |
| 4 | 2 | 2 | 1-of-4 | ½ | 119 | 190 |
| 5 | 2 | 2 | 1-of-4-2 | ½ | 59 | 94 |
| 6 | 4 | 4 | 1-of-4-2 | ¼ | 14 | 22 |

A data rate independent technique to increase the robustness of a communication link is the use of multiple receive channels. Each channel receives and detects the incoming signal. Demodulation and decoding will be done after the time and Doppler synchronized signal combination. The amount of received channels depends on the used hydrophone. Offered sensor solutions for the underwater telephone support up to four receive channels.

Based on these techniques and its combination a subset of six different MFSK configurations can be chosen by the operator of an underwater telephone. Thus, an adaptation of the communication link on the given channel and the desired application needs can be achieved. The different MFSK configurations can be seen in Table 1.

## Evaluation

To evaluate the proposed methods under real but reproducible conditions Wärtsilä ELAC Nautik made use of impulse responses that were recorded in several maritime areas under various environmental conditions. The impulse responses were recorded as part of the European Defense Agency (EDA) Project RACUN in 2010-2014 [1] by Italy, Netherland, Sweden and Norway. A list of sea areas is found in Table 2. The impulse responses are used to simulate the effects of the underwater channel for a test transmission with each MFSK configurations shown in Table 1. As a replay simulator, an adapted version of the acoustic communication channel simulator “Mime” of the Norwegian Defence Research Establishment FFI [2] was used. Necessary changes and functional enlargements were additionally done by Wärtsilä ELAC Nautik to get a full simulation and evaluation chain for the MFSK benchmark tests.

**Table 2:** Mapping of the measured impulse responses, the nation that recorded the data and the sea area of the measurement. Data recording was part of the EDA Project RACUN [1].

| Channel | Nation | Sea area |
|---|---|---|
| 1-12 | Italy | Coast of La Spezia |
| 13-17 | Netherlands | Norwegian Sea, south west of Bergen |
| 18-152 | Netherlands | Lyme bay Area, south England coast |
| 153-179 | Norway | Oslo Fjord |
| 180-213 | Sweden | South of Stockholm, Archipelago |

The evaluation of the produced data for every MFSK configuration is done with the underwater telephone Wärtsilä ELAC UT3000. In Figure 5 the results are shown. The bit error rate for every MFSK configuration (ordinate axis) and every sea area (abscissa axis) are indicated with five different colors. Figure 5 shows three plots with identical scenarios but different SNR. The Figure shows an SNR of 18 dB (top), 12 dB SNR (middle) and 6 dB SNR (bottom). MFSK configurations according to Table 1 were used. The less robust configuration shows the results with relatively high BERs and is increasing when lowering the SNR. However, with more robust configurations, the BERs are decreasing. It is noticeable, that the transmission in the channels 13-17 and 188-196 results, even with the most robust configurations, in high BERs. In this environments the transmissions were dominated by a relatively high amount of scattered reverberation and/or high frequency selective fading of the upper frequency band. Our tests indicate, that the demodulation and decoding of these data blocks are not the bottle neck why it failed. The communication mainly suffers from misdetection of the header block that indicates the beginning of a transmission. Improving the detection of the header in such reverberation and fading dominated environment is part of actual research.

In some scenarios, visible in Figure 5, it is noticeable, that at a given underwater channel, the "more robust" detection shows a higher BER than the "less robust". This can be explained due to the fact, that with increasing robustness the duration of the transmission increases. With increased duration of the transmission it is more likely that individual blocks of the whole transmission fail.

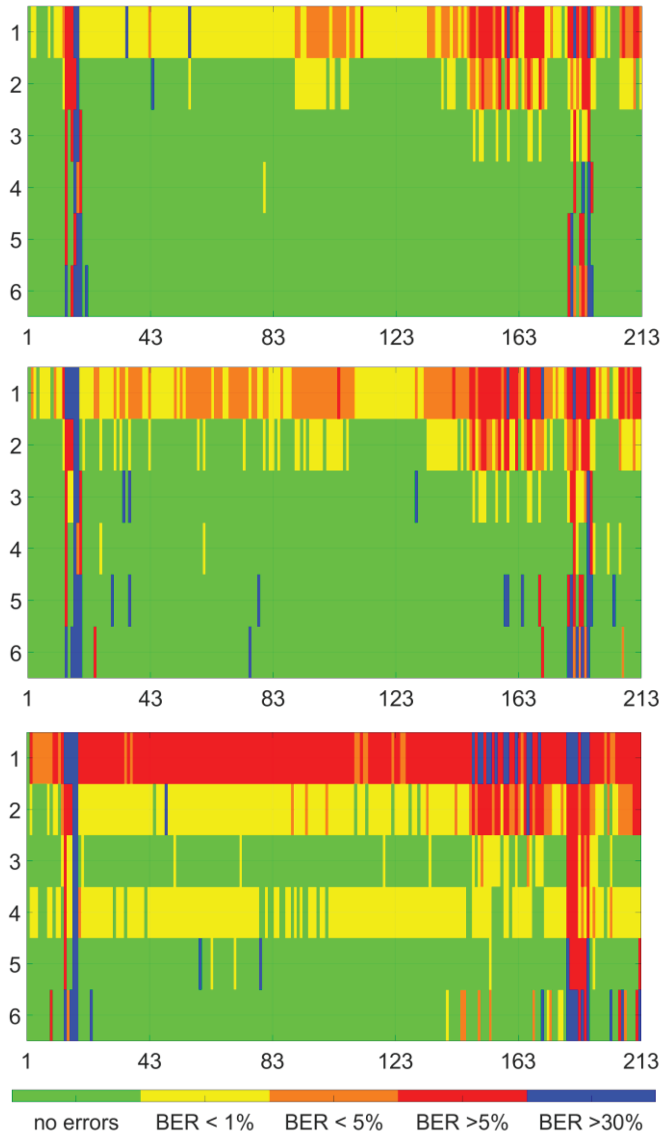


**Figure 5:** Bit-error rates (BER) of MFSK test transmissions with different configurations (ordinate axis) and different sea areas (abscissa axis). The figures show simulations with a SNR of 18 dB (top), 12 dB (middle) and 6 dB (bottom).

It is visible that special configurations, tailored to effects of the underwater sound channel, are needed for a robust and yet fast transmission. However, the conditions are highly variant and choosing the most robust transmission with the highest data rate is possible but highly situational.

## Conclusion and Outlook

In this paper Wärtsilä ELAC Nautik gave an overview of the demand and the challenges to perform acoustic digital communication through the underwater channel. The hydro-acoustic channel with its effects on transmitted signals were described. A physical layer solution and possible configurations to establish a robust horizontal communication link was presented. An evaluation of the method under different channel conditions could illustrate the context of robustness and data rate. It shows that not only one method with a fixed configuration for all applications and channels is sufficient. The variety and complexity of the underwater channel in different sea areas, at different times, under different water depths and other influencing factors lead to a continuous adaption need of available MFSK parameters.

The results of the evaluation illustrate the importance and challenge of a robust signal detection under strong time spreading and frequency selective channels.

Due to the complex and time varying underwater channel the operator needs a high degree of knowledge about the underwater channel and its influence on the chosen method and configuration. To reduce the degree of operator responsibility for choosing the correct configuration an exact information about the channel characteristics is needed.

Information about the actual channel can be determined directly by executing concrete channel measurements or indirectly by evaluating received communication signals. The results shall be provided to the operator. These are activities under development of Wärtsilä ELAC Nautik to continuously improve the underwater telephone ELAC UT3000.

Based on these results the next step for a cognitive communication approach is to derivate the optimal configuration under certain channel conditions and application needs. Thus results can be given to the operator as suggestions or via an automatic adjustment of the relevant parameters. Improvements of certain algorithms like the signal detector are part of the product roadmap to ensure a robust MFSK communication link even in the most challenging channels.

## Acknowledgement

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