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Performance of low-power underwater modem for shallow water communications

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Abstract The low-power underwater acoustic modem is usually an important component of the Underwater Wireless Sensor Network (UWSN). Network nodes have predetermined energy resources that will not be replenished during the life of the node. In shallow waters, multipath propagation is constantly occurring and for the modem to work effectively, solutions to overcome them must be used, which will also meet the important criterion of energy efficiency. The article presents the concept of a low-power underwater modem using Multiple Frequency-Shift Keying (MFSK) modulation and the fast frequency-hopping spread spectrum technique. In order to determine the performance of the modem, simulation tests were carried out using the Watermark simulator using the measured impulse responses of channels in shallow waters.

Keywords: MFSK, fast frequency hopping, low-power underwater acoustic modem, shallow water.

1. Introduction

Underwater acoustic modems are used in underwater devices that require communication with a master device or form an UWSN. If underwater devices operate in shallow waters, solutions should be used that allow for reliable operation of the modem in the event of multipath propagation. Such propagation causes that the transmitted signal is subject to reflections from the boundary surfaces of the underwater communication channel and objects in the water. The modem receiver receives signals from the direct path and from the paths obtained during reflections. As a result, we are dealing with selective fading at some frequencies of the used band. The movement of communication participants causes the Doppler effect, which significantly affects the efficiency of the underwater communication system. In turn, the limitation of the capacity of the hydroacoustic channel is caused by the small width of the available bandwidth and the low speed of propagation of acoustic waves [1].

Seasonal variability of conditions in underwater acoustic communication channels is a particular difficulty in unambiguous determination of their parameters and makes it impossible to develop universal underwater communication systems dedicated to all types of channels [2, 3].

A significant system limitation of the modem is the condition of energy efficiency, which requires the use of appropriate signals, algorithms for their digital processing and hardware solutions in its most important blocks. In particular, this applies to the wake-up receiver, which is responsible for the continuous reception of hydroacoustic signals and detecting among them the preamble signals of the transmitted data frame, as well as the receiver of the transmitted data. These solutions are to enable long-term and autonomous operation of the underwater device in which the modem as a priority device must ensure reliable communication. For this reason, a low-power single-chip processor was chosen to implement the modem instead of a digital signal processor (DSP) or an field-programmable gate array (FPGA) [4, 5].

The article presents the concept of a low-power underwater acoustic modem dedicated to an underwater device capable of long-term autonomous operation and ensuring reliable operation in shallow waters. The main topic of the work is to study performance of the considered modulation techniques using the Watermark simulator, which uses the measured impulse responses of channels in shallow waters. The solutions were selected to enable the implementation of the modem concept based on a low-energy single-chip processor.

2. Concept of modem – signals

The considered underwater acoustic modem transmits data based on a frame consisting of a preamble and data (Fig. 1). The preamble consists of pairs of pulses based on the Hyperbolic Frequency Modulation (HFM) signal with increasing (HFM-UP) and decreasing (HFM-DOWN) frequency during the pulse duration, this solution has already been tested by us both in terms of reliability and the possibility of low-power implementation [4, 6]. T_S specifies the duration of a single symbol, transmitted in a data block.

Due to energy limitations, incoherent modulated signals were used for data transmission, which are received in the receiver based on energy detection. Therefore, such systems do not need information about the carrier phase, and do not use the equalization method, which makes them easier to implement. However, in order to overcome the limitations of the underwater channel, it is necessary to take into account the relevant parameters, which will be presented in this chapter for the two selected modulation methods.

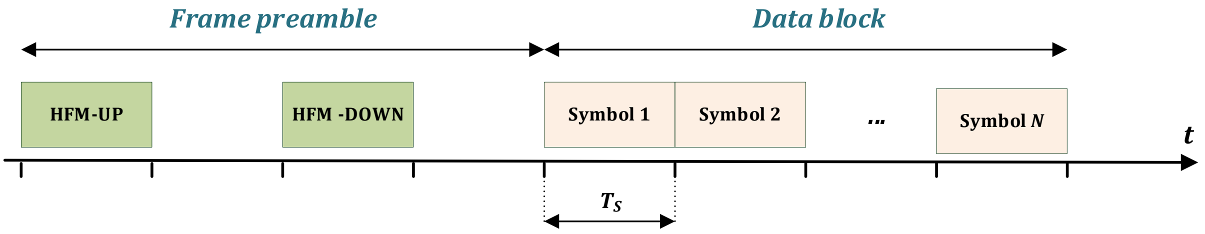

Figure 1. Frame of transmitted data.

It is planned to use the designed system to implement communication between the ship and the underwater device as shown in Figure 2. The hydroacoustic antenna is submerged from the ship to a predetermined depth, and the underwater object is located on the bottom and can be buried in bottom sediments.

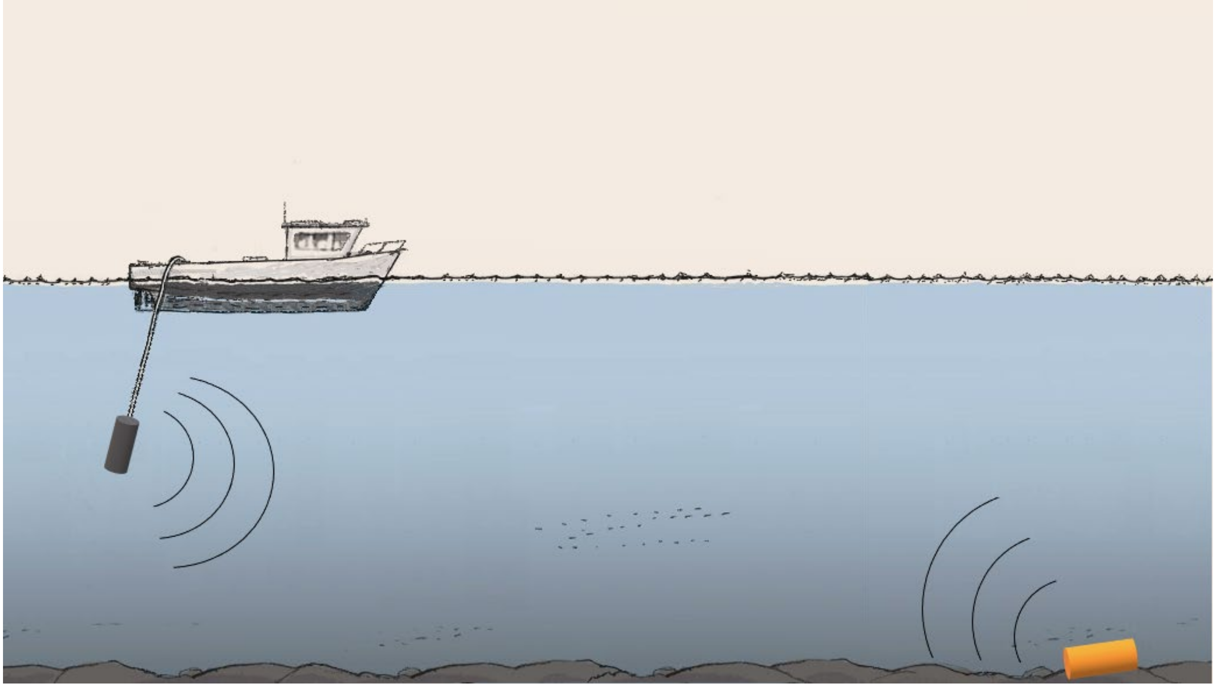

Figure 2. Scheme of operation of the designed underwater communication system.

2.1. Use of Multiple Frequency-Shift Keying (MFSK) modulation

The first method of signal transformation considered for transmitting data in the channel is based on the MFSK modulation [7, 8].

In the case of a shallow water communication channel that uses MFSK modulation, it is required to use pauses between successively transmitted symbols. The pauses are called guard times. The need to use guard times results from the need to avoid intersymbol interferences, which arise as a result of the reverberation phenomenon, in particular its main component, which is the multipath phenomenon. The reason for intersymbol interference is the elongation of the pulses, and as a result, the preceding pulses overlap with the next ones. The length of the guard times used is at least equal to the maximum delay spread T_m of the channel [8, 9]. The maximum delay spread T_m is the time between the first and last components of the received multipath signal. The condition $T_m \leq T_G$ must be met, and at the same time $T_m << T_s$, where T_G means the duration of the guard time and T_S means the duration of the symbol. The scheme of operation of the system with multiple frequency keying 16-FSK, which takes into account the use of guard times, is shown in Fig. 3.

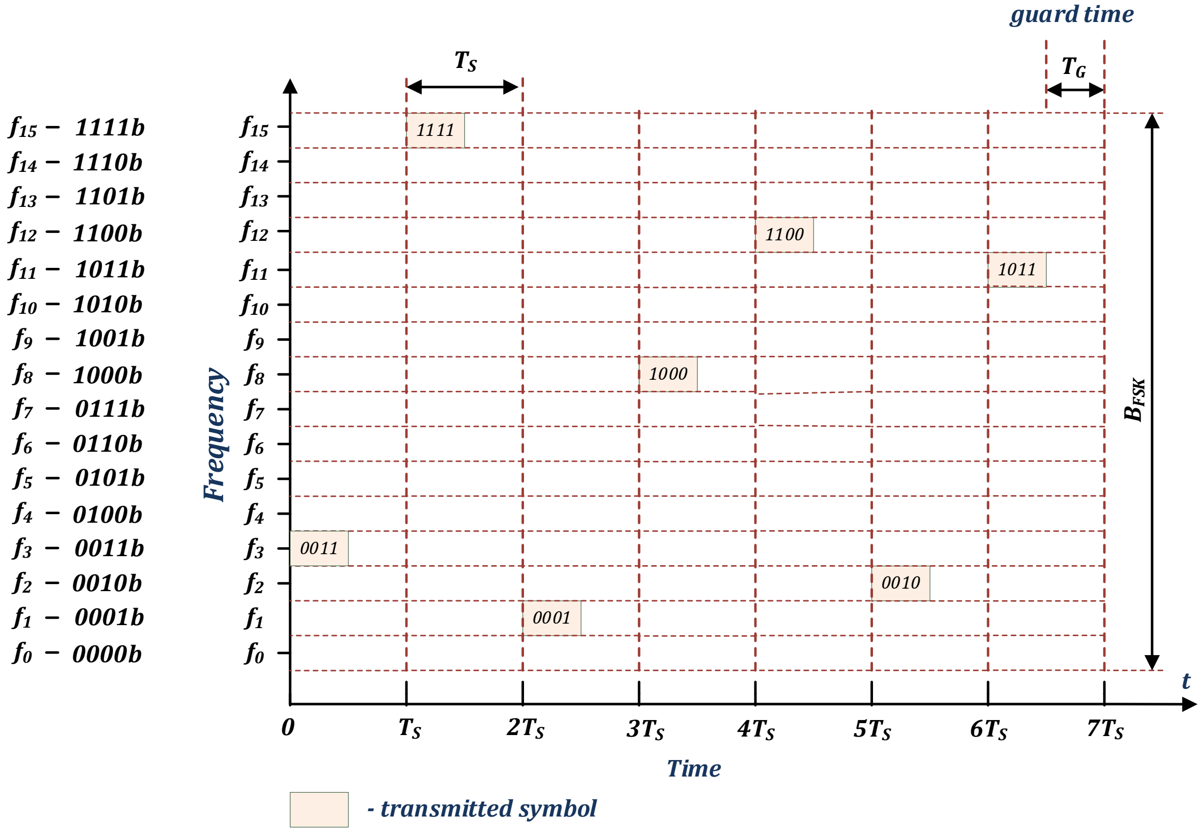

Figure 3. Diagram of system with 16-FSK and guard times between transmitted symbols.

The form of the transmitted low-band FSK signal can be represented by the following formula [11]:

$$s_m(t) = \sqrt{\frac{2E_s}{T_s}} \cos[2\pi f_m t + \varphi_m] \quad , \tag{1}$$

$$(n-1)\,T_S \leq t \leq nT_S - T_G \;, \quad 1 \leq n \leq N \;, \quad 0 \leq m \leq M-1 \;,$$

where E_s/T_s is the power of the transmitted signal, E_s is the energy per FSK symbol, f_m is the m-th characteristic frequency, φ_m is the unknown random phase associated with the m-th pulse, and N is the number of all words to be transmitted. All transmitted signals are characterized by the same values of these parameters.

To prevent the influence of the Doppler effect, which manifests itself as Doppler deviation, it is necessary to specify the bandwidth reserved for a particular signal with a specific characteristic frequency. Therefore, the condition $B_d << B_s$, must be met, where B_d means the maximum Doppler spread and B_s means the bandwidth of the transmitted symbol [8-10]. For a data transmission system with the carrier frequency f_c = 14 kHz, the band B_{FSK} = 4 kHz and the maximum allowable Doppler speed $v_{d,max}$ = 5 m/s (~10 knots), the following maximum Doppler deviations $f_{d,\max}$ = 40 Hz are obtained at the ends of this assumed operating band f_c-Δ_{2kHz} = 12 kHz and $f_{d,\max}$ = 53.3 Hz for f_c+Δ_{2kHz} = 16 kHz. To meet the orthogonality condition, it is required to use a minimum separation between significant frequencies of Δf or a multiple thereof, where $\Delta f = 1/T_s$. To ensure adequate frequency separation so that the Doppler effect does not degrade the band of adjacent significant frequencies, it is required to use the minimum bandwidth for a single significant frequency equal to $B_S = \Delta f$. Therefore, for 8-FSK modulation and pulse length T_s = 4 ms which gives B_S = 250 Hz, it is required to use a bandwidth of $B_{FSK} = 8\cdot\Delta f$ = 2000 Hz. On the other hand, for 16-FSK modulation and pulse length T_s = 4 ms which gives B_S = 250 Hz, it is required to use a bandwidth of $B_{FSK} = 16\cdot\Delta f$ = 4000 Hz.

The reception is carried out by a non-coherent receiver, which does not require the current determination of the reference phase and is based on the energy detection method. At the receiver, the signal is converted to a baseband signal with a specific B_{FSK} bandwidth. Due to energy constraints, this operation is performed by analogue processing. Signal samples obtained by analogue-to-digital conversion are used for signal detection. A windowing operation is performed on the samples using the selected window type, and then the signal is processed by calculating the discrete Fourier transform. The result of the transform is a discrete spectrum of the signal, which is then used to determine the power density spectrum of the discrete signal for successive symbol durations T_s. The spectrum of the signal is obtained in the form of bands, defined by Y_m values, where each band represents a narrow band corresponding to the expected significant frequency f_m (m = 0, ..., M-1). In the decision system, on the basis of the $f_m = \max(Y_m)$ criterion, the appropriate FSK symbol is assigned.

2.2. Using the technique of Fast Frequency Hopping (FFH)

An alternative method of signal transformation is the frequency hopping technique with Binary Frequency-Shift Keying (BFSK) modulation [7, 11-12]. In this technique, the change of the carrier frequency occurs many times during the duration of the symbol T_S . The available channel bandwidth is divided into adjacent frequency sub-channels. The carrier frequency between the sub-channels is switched L times during T_S using a selected code sequence that is known to both the transmitter and the receiver.

At the transmitter, the transmitted symbol is passed to the FSK modulator, which converts the transmitted symbol of duration T_S into a signal of the appropriate frequency for the sub-channel depending on the applied FSK modulation order and for a duration equal to the single hop time T_H (also known as dwell time), according to $T_s = LT_H$. Then, such a signal, after amplification, is sent through the communication channel via a hydroacoustic transducer. On the receiving side, the signal from the hydroacoustic transducer is amplified in the preamplifier and transmitted to the receiver. At the receiver, the signal is shifted to the baseband and then FSK demodulation is performed. Figure 4 shows a diagram of a fast frequency hopping system for an example code sequence pattern.

In order to ensure the required orthogonality between the tones of the FSK modulation signal, the minimum distance between them, which is a multiple of $f_H = 1/T_H$, should be used. This property will ensure that there is no crosstalk with the other hopping frequency bands.

The form of the transmitted low-band FFH-FSK signal can be written as:

$$s_n(t) = \sqrt{\frac{2E_S}{T_S}}\cos\left[2\pi(f_l + f_m)t + \varphi_n\right] \ ,$$
$$\left[(n-1) + \frac{l-1}{L}\right]T_S \le t \le \left[(n-1) + \frac{l}{L}\right]T_S \ , \quad 1 \le n \le N \ , \quad 1 \le l \le L \ , 0 \le m \le M-1 \ , \tag{2}$$

where E_S/T_S is the power of the transmitted symbol signal, T_S is the duration of the symbol signal, l is the hop number, f_l is the intermediate frequency for the selected band of the l-th frequency hopping, f_m is the m-th characteristic frequency, φ_n is the unknown random phase associated with the transmitted symbol, n is the number of the transmitted word, M is the FSK modulation order, and N is the number of total symbols to be send.

The FFH technique uses diversity technique which is a hybrid of time and frequency diversity. Typically, time diversity performs multiple transmissions and receptions of the same symbol over time. In the FFH technique, for a channel with *fast fading*, the time interval T_{cc} between the transmission of successive symbol signals of T_H duration at the same hop frequency is required to be longer than the channel coherence time T_c ($T_H > T_c$).

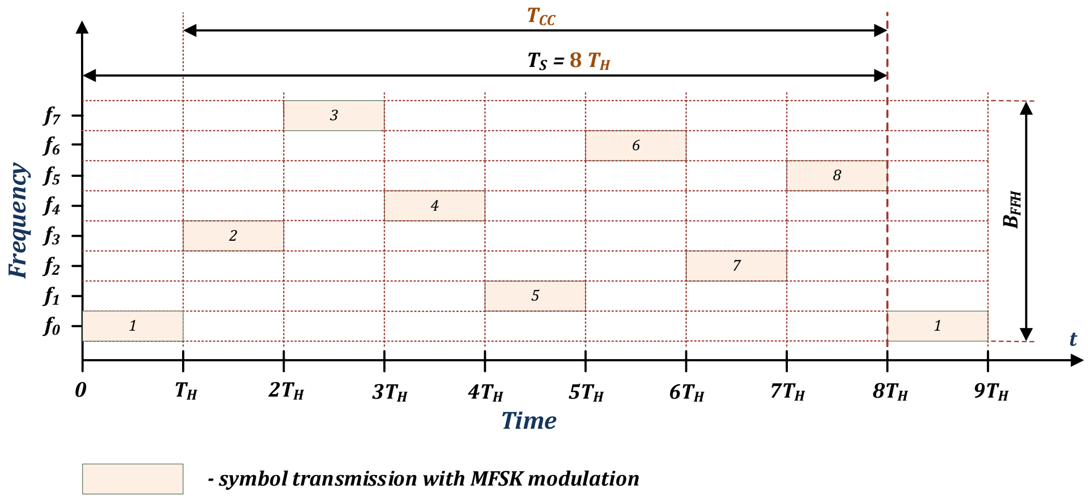

Figure 4. Diagram of the fast frequency hopping technique for an example code sequence pattern of length 8 ($T_S = 8 \cdot T_H$).

This allows two hops to the same frequency to be mutually independent in the time domain. In general, the time interval T_{cc} is the time during which the used hopping frequencies are not used and this allows for the attenuation of multipath components present in the hopping frequency band. This is achievable provided that the multipath delay spread T_m is shorter than the time interval T_{cc}. If the hop duration T_H is shorter than the coherence time of the channel T_c ($T_H < T_c$) then the channel is with a *slow fading* and the fade is constant during a single hop and then changes in signal amplitude caused by the presence of fades are constant for a single hop. In turn, frequency diversity is usually based on transmitting and receiving the same symbol on multiple carrier frequencies at the same time, but adjacent carrier frequencies must be separated by a band greater than the coherence band B_c of the channel and it is assumed that independent fading occurs in the case of a frequency selective channel.

Time diversity and frequency diversity operate sequentially because the redundant symbols of hop time T_H are received individually at a certain time and use the selected carrier frequencies. The degree of reception redundancy increases with the order of diversity as well as also increases the average signal energy.

If the interval between adjacent hopping frequencies is smaller than the coherence band B_c of the channel ($1/T_H < B_c$), then the transmission system takes place in the channel with fading. Then, through a clever jump pattern design, it is possible to avoid this adverse inequality.

When $T_H > T_m$, the channel exhibits *flat fading* and therefore allows the effects of multipath propagation to be ignored. On the other hand. for $T_H < T_m$ the channel is *frequency selective* and the FFH technique aims to remove the effects of multipath effects affecting the signal being analysed in the receiver. In the receiver, after a reception time equal to the hop duration T_H when the multipath components start to arrive at the receiver, hops to the new hop frequency. Since the incoming multipath components occupy a band other than the currently received signal, the effect of interference is negligible.

Taking into account the influence of the Doppler effect, it is necessary to select the interval between the significant frequencies in accordance with the principles discussed for MFSK modulation, where T_S should be replaced by T_H.

In the reception process, the received signal is subjected to analogue-to-digital conversion, and then the selected band signal with a certain B_{FFH} width is shifted to the baseband. The obtained discrete samples for successive T_H durations are used to determine the power density spectrum. These operations are identical to those performed in the MFSK receiver, but obtained spectrum covers the entire B_{FFH} band. This band includes all branches corresponding to the characteristic frequencies of the MFSK modulation and all possible hops L, hence the number of all analysed branches is $L \cdot M$. The spectrum for this band is determined for each of the L possible hops, and the extracted spectral lines for each hop $Y_{m,k}$ (m = 0,...,M-1; k = 1,...,L) form a detection matrix $W_{m,k,l}$ (m = 0,...,M-1; k = 1,...,L, k = 1,...,L) of size $(L \cdot M) \cdot L$. The detection matrix enables the focusing operation of the spread signal spectrum according to the selected reception diversity algorithm and according to the hopping pattern determined on the basis of a known code sequence. As a result, a vector of decision values Z_m is obtained, and then an appropriate MFSK symbol is assigned to it.

As the reception diversity algorithm, a square-law with equal gain combining algorithm was chosen. It performs soft-decision decoding and consists in summing L values of $W_{m,k,l}{}^2$, according to the selected hopping pattern, which can be written as formula:

$$Z_m = \sum_{l=1}^{L} W_{m,k,l}{}^2. \quad (3)$$

In the receiver of the considered low-power modem receiver, detection is based on the FFT (Fast Fourier Transform) algorithm, the computational complexity of which is $N \cdot \log_2 N$. The transform for the MFSK technique is calculated for N samples collected at time T_S, and for the FFH technique at time T_H. The difference results from the need to use a combining algorithm for the FFH technique, which sums the values over L hops for the total symbol duration T_S.

3. Simulation tests

The Watermark simulator [13] was used to conduct simulation tests involving data transmission through an underwater acoustic channel of shallow waters. It allows to determine the quality of data transmission in the channel in the presence of multipath propagation and the Doppler effect. It is a shell around the validated channel simulator Mime based on impulse responses measured in the sea [14, 15]. The simulator convolves input signals with the measured channel's impulse response and this operation is given by:

$$y(t) = \int_{-\infty}^{\infty} \hat{h}(t,\tau)x(t-\tau)d\tau \ + n(t), \quad (4)$$

where $x(t)$ is the input user signal, $\hat{h}(t,\tau)$ a time-varying impulse response, $n(t)$ a noise term, and $y(t)$ distorted output signal.

For the simulation tests, two communication channels included in the simulator and made available as impulse responses measured in Norway-Oslofjord (NOF1) and Norway-Continental Shelf (NCS1) were used. The impulse responses were measured between a stationary projector and a stationary receiving hydrophone placed on the bottom. Measurements were performed in the Single-Input Single-Output (SISO) configuration. Parameters of NOF1 and NCS1 channels and signal are presented in Table 1.

Table 1. Parameters of the Watermark channels and the signal [16].

Parameter	NOF1	NCS1
Environment	Fjord	Shelf
Time of year	June	June
Range	750 m	540 m
Water depth	10 m	80 m
Transmitter/Receiver deployment	Bottom	Bottom
Type of configuration	SISO	SISO
Centre frequency	14 kHz	14 kHz
Bandwidth	8 kHz	8 kHz
Doppler coverage	7.8 Hz	31.4 Hz

The NOF1 channel is a shallow region of the Oslofjorden, and it is typified by relatively stable arrivals. In turn, the NCS1 channel has no stable subsequent arrivals. The multipath delay spread T_m for both channels is similar and amounts to approximately 12 ms [8,16]. As first, the Bit Error Rate (BER) for data transmission using BFSK modulation without using guard times was determined. Tests were made for different symbol durations T_S and SNR in both channels, and the results are summarized in Table 2. A distance between characteristic frequencies of Δf = 250 Hz was determined, thus the entire B_{FSK} bandwidth is 500 Hz for BFSK modulation, and 4000 Hz for 16-FSK modulation. The tests were performed for the BFSK, 4-FSK, 8-FSK and 16-FSK modulations, but only the results for the BFSK modulation are presented, due to the fact that among them, the BFSK modulation is characterized by the highest BER values, which are the upper limit of the possible values. In turn, Table 3 contains the obtained BER for data transmission with BFSK modulation with using guard times for similar parameter values.

Figure 5 shows the signal transmitted with BFSK modulation without using guard times for bits "01", the signal received after transmission over the NOF1 channel and the NCS1 channel for the duration symbol T_S = 16 ms and SNR = 20 dB.

Table 2. Determined BER for data transmission with BFSK modulation over NOF1 and NCS1 channels, without using guard times.

T_S [ms]	SNR [dB]	NOF1 channel BER	NCS1 channel BER
4	20	0.1137	0.3643
	10	0.1138	0.3743
	0	0.1338	0.3743
8	20	0.0250	0.2240
	10	0.0253	0.2243
	0	0.0270	0.2298
16	20	0.0195	0.1815
	10	0.0197	0.1816
	0	0.0223	0.1835
32	20	0.0092	0.1377
	10	0.0098	0.1378
	0	0.0097	0.1390

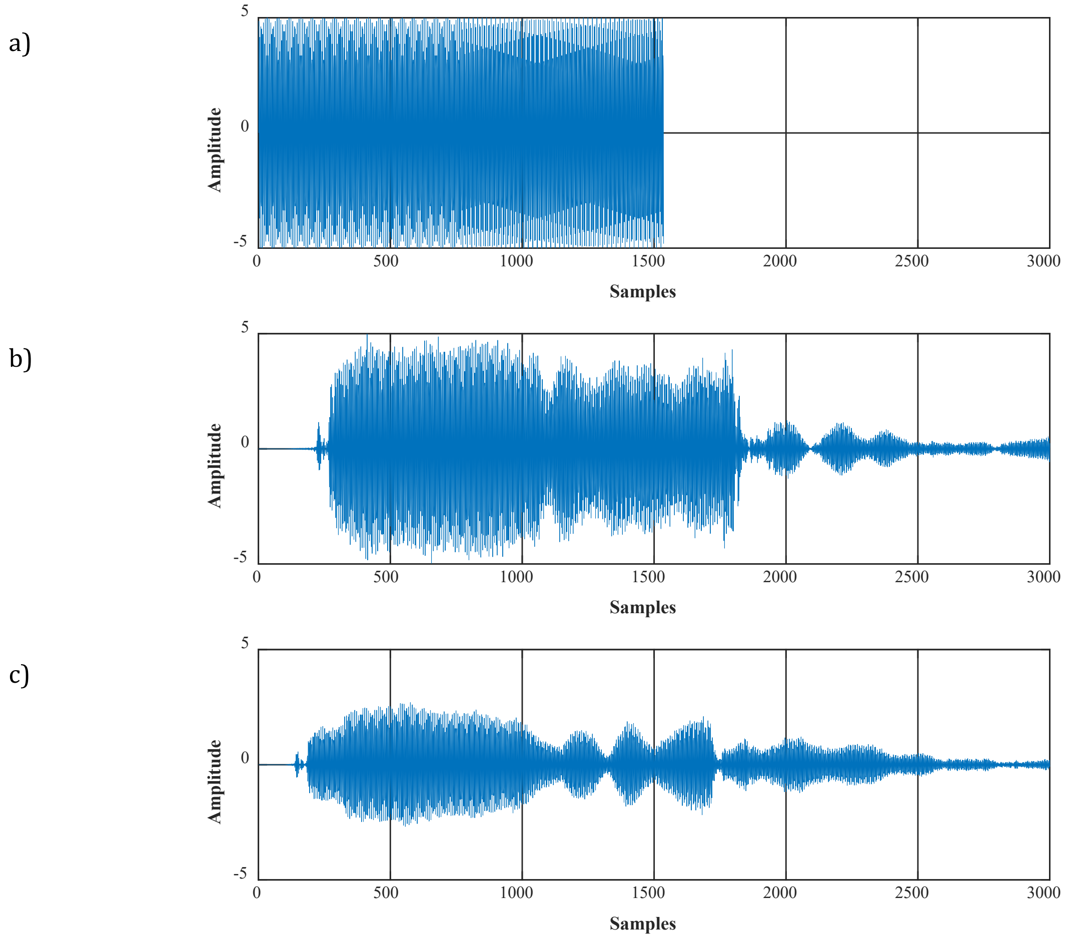

Figure 5. Signals with BFSK modulation for bits 01: a) transmitted, b) signal after transmission over NOF1 channel, c) signal after transmission over NCS1 channel (T_S = 16 ms, SNR = 20 dB).

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Table 3. Determined BER for data transmission with BFSK modulation over NOF1 and NCS1 channels, with using guard times (SNR=20dB).

T_S [ms]	T_G [ms]	SNR [dB]	NOF1 channel BER	NCS1 channel BER
4	4	20	0.0298	0.1883
		10	0.0305	0.1892
		0	0.0352	0.1958
8	8	20	0.0020	0.1107
		10	0.0021	0.1120
		0	0.0032	0.1167
16	16	20	0.0013	0.0318
		10	0.0015	0.0319
		0	0.0022	0.0328
32	32	20	0.0006	<0.0001
		10	0.0010	<0.0001
		0	0.0022	<0.0001

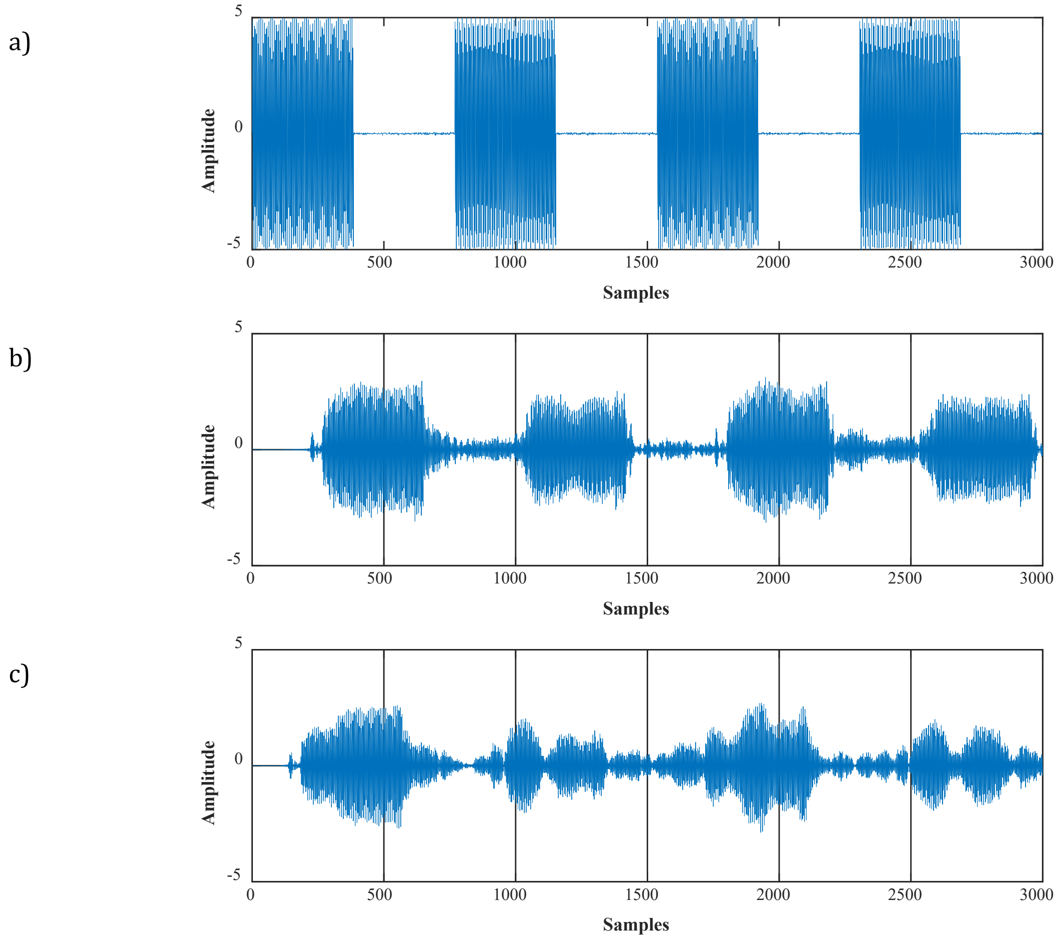

Figure 6. Signals with BFSK modulation with using guard times for bits 0101 : a) transmitted, b) signal after transmission over NOF1 channel, c) signal after transmission over NCS1 channel (T_S = 8 ms, T_G = 8 ms, SNR = 20 dB).

The tests confirmed that the use of guard times improves the transmission quality more effectively than just extending the duration of the symbol duration T_s. The comparison of the results shows that the effects of multipath propagation degrade transmission quality more than the noise level. For the NOF1 and NCS1 channels, the maximum delay spread T_m is about 12ms and in the case of transmission without guard times, the transmission with pulses of 4ms does not allow for satisfactory results.

The fast frequency hopping spread spectrum technique FFH uses BFSK modulation, and the choice is dictated by bandwidth constraints. For the BFSK modulation used, the interval between the significant frequencies was set equal to Δf = 250 Hz, which ensures that the maximum Doppler deviation $f_{d,max}$ of 125 Hz is taken into account. Since the hops between the available subbands during the transmission of a single symbol are made according to a fixed pattern, their maximum number during the tests was set at L = 8. The applied frequency spacing requires the use of a subband with a width of $B_{BFSK} = 2 \cdot \Delta f = 500$ Hz, which with the maximum number of hops equal to L = 8 gives the system bandwidth equal to B_{FFH} = 4000 Hz. During signal detection, a periodogram calculated for each hop time T_H and a linear cumulative diversification algorithm are used.

Data transmissions were tested with the number of hops L = {2, 3, 4, 5, 6, 7, 8} and for the hop duration T_H = {4 ms, 8 ms, 16 ms}. Two patterns of carrier frequency hopping were considered: sequential ([$f_0\, f_1\, f_2\, f_3\, f_4\, f_5\, f_6\, f_7\, f_0\, f_1\, f_2$...]) and pseudo-random ([$f_0\, f_3\, f_7\, f_4\, f_1\, f_6\, f_2\, f_5\, f_0\, f_3\, f_7$...]). The results of the FFH technique tests are presented in Table 4.

Table 4. Determined BER for data transmission with FFH technique BFSK modulation over NOF1 and NCS1 channels.

Order of diversity L	T_S [ms]	SNR = 20 dB		SNR = 0 dB	
		NOF1 channel BER	NCS1 channel BER	NOF1 channel BER	NCS1 channel BER
2		0.1733	0.1787	0.1678	0.1719
3		0.0990	0.1555	0.1085	0.1556
4		0.0293	0.1507	0.0412	0.1499
5	4	0.0166	0.1420	0.0264	0.1395
6		0.0101	0.1274	0.0231	0.1325
7		0.0064	0.0901	0.0175	0.1000
8		0.0038	0.0851	0.0113	0.0924
2-8	8	<0.0001	<0.0001	<0.0001	0.0003
2-8	16	<0.0001	<0.0001	<0.0001	<0.0001

The results obtained for both sequential and pseudo-random patterns are similar, which may be related to the small number of available hops or large intervals between significant frequencies. Transmissions with errors were obtained only for the hop duration T_H = 4 ms for both channels, and for T_H = 8 ms in NCS1 channel, in the case of SNR = 0, L = 2. The obtained BER values indicate the advantage of the FFH technique with BFSK modulation over the MFSK modulation using guard times.

4. Conclusions

The article presents the concept of a low-power underwater modem, with emphasis on the analysis of modulation techniques enabling reliable communication in shallow water. For these two modulation techniques, methods for eliminating the influence of multipath propagation and the Doppler effect are described in detail.

Simulation tests were performed with the Watermark simulator, which uses impulse responses measured in Norway-Oslofjord (NOF1) and Norway-Continental Shelf (NCS1). The multipath delay spread T_m for these channels is about 12 ms. Simulator allowed to determine the efficiency of selected modulation techniques in such difficult channels and to select optimal values of transmission parameters. For BFSK modulation without using guard times transmission over NCS1 channel and all analysed the duration symbol T_S and SNR, is burdened with significant errors, and only over NOF1 channel and T_S = 32 ms BER values of approximately 10^{-2} were obtained. BFSK modulation with using guard times allows for much better transmission quality, i.e. BER of approximately 10^{-3} already for T_S = 16 ms, T_G = 16 ms over NOF1 channel and error-free transmission over NCS1 channel. Using the FFH technique, the best transmission quality results were obtained. For a minimum of L = 2 and the duration symbol T_S = 8 ms, error-free transmission was achieved for the NOF1 channel and few errors for the NCS1 channel with SNR = 0 dB.

The results of the tests indicate that the fast frequency hopping technique should be used first in modems intended to operate in such a difficult propagation environment.

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Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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