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Research Paper

Shallow Water Experiment of OFDM Underwater Acoustic Communications

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The large variability of communication properties of underwater acoustic channels, and especially the strongly varying instantaneous conditions in shallow waters, is a challenge for the designers of underwater acoustic communication (UAC) systems. The use of phase modulated signals does not allow reliable data transmission through such a tough communication channel. However, orthogonal frequency-division multiplexing (OFDM), being a multi-carrier amplitude and phase modulation technique applied successfully in the latest standards of wireless communications, gives the chance of reliable communication with an acceptable error rate. This paper describes communication tests conducted with the use of a laboratory model of an OFDM data transmission system in a shallow water environment in Wdzydze Lake.

Keywords: underwater acoustic communications; UAC; orthogonal frequency-division multiplexing; OFDM.

1. Introduction

The transmission properties of an underwater acoustic communication channel (UAC) are strongly determined by the specificity of its geometry, geographical location, the bottom type of the basin, and the weather conditions. In addition, UAC channel properties can change over time – during the day or over the year. Thus, the signals transmitted in UAC systems suffer from time-variability of multipath propagation conditions (KOCHAŃSKA *et al.*, 2016). Moreover, a UAC channel cannot always be described as wide-sense stationary with uncorrelated scattering (WSSUS), as is commonly assumed in the case of radio-communication channels (KOCHAŃSKA *et al.*, 2018; SKLAR, 1997).

UAC system designers, mainly working based on standard simple phase and frequency keying schemes, became interested in the OFDM technique, especially due to the fact that in modern radio-communication systems, such as LTE cellular telephony and DVB-T digital television, parameters of the OFDM data transmission protocol are adapted to the current conditions of the link. The popularity of this modulation technique results mainly from the fact that it allows a high bit rate to be obtained, while limiting the distortion of the received signal caused by the multipath propagation phenomenon. In addition, the OFDM technique allows for flexibility of the parameters of the transmitted signal, such as the signalling scheme and the duration of the modulation symbol (ZHOU, WANG, 2014).

Achievements in the field of underwater OFDM systems include both direct implementations of algorithms used in radio communication systems as well as new time-and-frequency synchronisation techniques and UAC channel estimation. In (FRASSATI *et al.*, 2005), the results of experimental tests of an OFDM modem in an 80 m deep channel over a distance of 6 km are described. Reliable transmission was obtained at 800 bps in the 3–5.5 kHz channel band characterised by a 40 ms delay spread and a variation of the Doppler shift of 3 Hz. Another system operating in a shallow channel is shown in (COATELAN, GLAVIEUX, 1995). At a distance of 1 km and a depth of 100 m, an effective rate of 250 bps was achieved with an error rate of 10^{-3}. In (BRADBEER *et al.*, 2003), an OFDM system operating in the 43–53 kHz band is described, in which un-encoded data were transmitted at a rate of 10 kbps with the error rate of less than 5%. The channel was 820 m long and 10 m deep. In the system described in (CHITRE *et al.*, 2005), a 24 kHz band is divided into 64 sub-channels. The system was tested in a horizontal channel at a range of 350 m. The obtained transmission rate was even 48 kbps. However, in this case, the bit error rate was not less than 10^{-1} (a BER of less than 10^{-3} was obtained after applying a channel coding technique, reducing the transmission rate to 5.3 kbps). In (Stojanovic, 2006), the results of experimental tests using the OFDM system are described. Transmission for 128, 256, 512, 1024, and 2048 sub-channels located in the 24 kHz frequency band was tested in a 2.5 km long horizontal shallow channel. In (Nissen, 2005), the results of pilot-based OFDM transmission in the south-west approach between England and France, from a surface ship to a submarine, are described. Communication was established at a distance of 25 km. It was the longest distance on which OFDM transmission has been carried out underwater. The mentioned publications describe communication experiments in both: deep and shallow, horizontal and vertical channels. However, there are only a few reports from experiments carried out in very shallow waters.

The OFDM technique is being implemented in a laboratory model of an acoustic data transmission system, designed at the Department of Sonar Systems, Faculty of Electronics Engineering, Telecommunications, and Computer Science, Gdansk University of Technology. The motivation is to achieve reliable data communication in very shallow waters, with the best possible performance in tough propagation conditions.

2. Structure of communication signal

The transmitter used in the laboratory model of an OFDM data transmission system generates an OFDM signal within a band of 5 kHz, occupying the frequency range from 27.5 kHz to 32.5 kHz. Each of the signal frames starts with a synchronisation sequence, being a pseudo-random binary sequence (PRBS). Typically, OFDM systems use frame synchronisation based on the OFDM symbol cyclic prefix (CP) (Zhou, Wang, 2014). However, in the case of radio and acoustic systems operating in difficult propagation conditions, a synchronisation technique based on correlation reception of PRBS sequences is also used. In (Qingfeng *et al.*, 2014), a synchronisation algorithm based on a pseudo-noise (PN) sequence preamble was compared with the traditional algorithm based on CP. The former turned out to be more accurate and stable than the latter. As is described in (Tufvesson *et al.*, 1999), application of a PN-based preamble makes it possible to use a lower detection threshold in the OFDM receiver, which results in a lower false detection probability and a lower probability of missing the synchronization signal. Moreover, the peak-to-average power ratio for a PN-based preamble is low, which results in a sharp synchronisation peak, as opposed to conventional preambles based on repeated OFDM symbols. In (Stojanovic, 2006), a PN sequence of the length 127 is used as the OFDM frame preamble. Another advantage of using the PN sequence for frame synchronisation is the possibility of using it simultaneously for channel estimation. In (Zhenrui *et al.*, 2013), a joint synchronisation and Doppler scale estimation method with time domain synchronous OFDM for underwater acoustic communication is proposed.

In the OFDM system model proposed in this paper, an m-sequence of rank 8 is used as the frame synchronisation sequence, which modulates the carrier frequency of f_c = 30 kHz. The sequence is repeated 20 times and its duration is T_{synch} = 1.02 s. The PRBS sequence is followed by the OFDM signal of duration of 2.5 s which is composed of K modulation symbols.

The process of OFDM signal generation is shown in Fig. 1. The input data stream is formed into complex BPSK constellation symbols. Next, each OFDM frequency domain symbol is composed of N_s samples, of which N_b samples are BPSK symbols and the remaining $N_s - N_b$ samples are zeros. The ratio between N_s and N_b is 40, which corresponds to the ratio of the transmission bandwidth B = 5 kHz and the sampling frequency f_s = 200 kHz.

Frequency domain symbols are processed by IFFT to obtain time-domain symbols, each of duration T_{OFDM}. Each of them is extended by the cyclic prefix of duration T_g equal to $\frac{1}{4}$ of T_{OFDM}. Such prepared OFDM symbols preceded by a synchronisation preamble modulate the carrier wave of frequency f_C = 30 kHz.

The OFDM signal basic parameters are shown in Table 1. Depending on the number of subcarriers N_s, different subcarrier spacing B_s is used. This determines the duration $T_{\text{OFDM}} = 1/B_s$ of a single OFDM symbol. After prepending a cyclic prefix, the symbol duration is $T_S = T_{\text{OFDM}} + T_g$. For example, if the number of sub-channels for data transmission is N_B = 16, then the spectrum of the OFDM signal is divided into N_s = 640 sub-channels. The subcarrier spacing is equal to $B_s = \frac{F_s}{N_s}$ = 312.5 Hz. Thus, 16 sub-channels for data transmission occupy bandwidth $B = 16 \cdot 312.5$ Hz = 5 kHz. The duration of a single OFDM symbol is equal to $T_{\text{OFDM}} = \frac{1}{B_s}$ = 3.21 ms and after prepending a cyclic

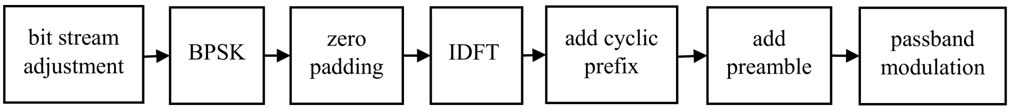

Fig. 1. Process of OFDM signal generation.

Table 1. OFDM signal parameters.

No of subcarriers N_s	No of subcarriers N_B in $B = 5$ kHz	Subcarrier spacing B_s [Hz]	Symbol duration T_{OFDM} [ms]	Symbol duration with CP T_S [ms]	Symbols per frame
160	4	1250.0	0.80	1.00	2500
320	8	625.0	1.60	2.00	1250
640	16	312.5	3.21	4.01	625
1280	32	156.3	6.41	8.01	312
2560	64	78.13	12.82	16.03	156

prefix $T_s = 4.01$ ms. Depending on the number of subcarriers, a different number of symbols K is transmitted at a fixed time of 2.5 s. The amount of information that can be transmitted in each frame is fixed and equal to 10 kbits.

3. Pilot tones

The OFDM signal transmitted through a UAC channel with strong multipath propagation suffers from selective fading observed in the frequency-domain (Sklar, 1997). In order to minimise the selective fading phenomenon, some of the subcarriers are used as reference pilot tones to equalise the signal spectrum in neighbouring subchannels. Two pilot tone patterns were implemented in a laboratory model of a UAC system.

Pattern 1

In the first case, the pilot tones are sent as every second subcarrier (Fig. 2a). A correction coefficient C_H was calculated on the basis of a complex value of a given pilot tone at the transmitter and receiver sides:

$$C_H[k, f_n] = \frac{H_{TX}[k, f_n]}{H_{RX}[k, f_n]}, \qquad (1)$$
$$f_n = 0, 2, 4, ..., N-2; \qquad k = 0, 1, 2, ..., K-1,$$

where $C_H[k, f_n]$ is the correction coefficient for pilot tone number f_n and symbol number k, $H_{TX}[k, f_n]$ is the value of transmitted pilot tone number f_n and symbol number k, $H_{RX}[k, f_n]$ is the value of received pilot tone number f_n and symbol number k.

Next, the values of C_H are used to correct the values of the neighbouring subcarriers. This is done in two ways. In the first case, the $H_{RX}[k, f_n+1]$ subcarrier is corrected by the C_H correction value for one neighbouring subcarrier:

$$\widehat{H}_{RX}[k, f_n+1] = H_{RX}[k, f_n+1] \cdot C_H[k, f_n]. \qquad (2)$$

In the second case, $H_{RX}[k, f_n+1]$ is corrected by the mean value of two neighbouring C_H coefficients (except for the $H_{RX}[k, N-1]$ tone, which is only corrected by $C_H[k, N-2]$ correction coefficient):

$$\widehat{H}_{RX}[k, f_n+1] = H_{RX}[k, f_n+1] \cdot \left(\frac{C_H[k, f_n] + C_H[k, f_n+2]}{2}\right).$$

Each OFDM subcarrier is modulated by the BPSK scheme, thus the signal spectrum amplitude on each subcarrier remains constant. The pilot tones are used to correct the phase of subcarriers for data transmission. Phase distortion can be caused by underwater noise and both inter-symbol interference (ISI) if the transmission takes place in multipath propagation conditions, and inter-channel interference (ICI) if the transmission takes place in a non-stationary channel with a significant distribution of Doppler shift.

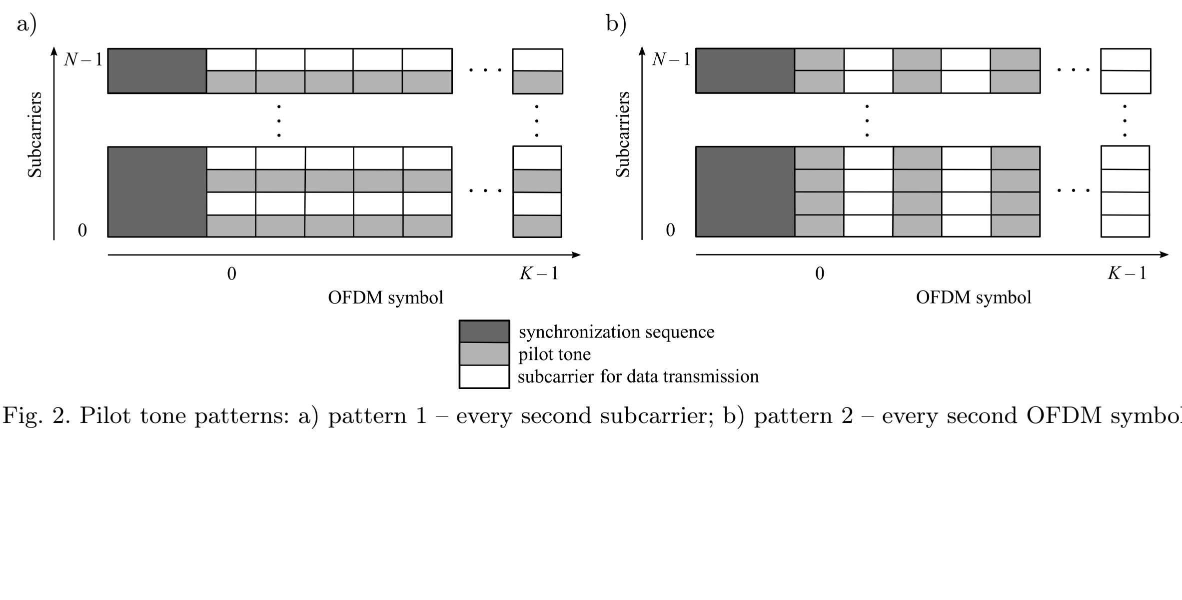

Fig. 2. Pilot tone patterns: a) pattern 1 – every second subcarrier; b) pattern 2 – every second OFDM symbol.

Pattern 2

The second pattern of the pilot tone arrangement is that all subcarriers are either pilot tones or data tones in every second OFDM symbol (Fig. 2b):

$$C_H[k,f_n] = \frac{H_{TX}[k,f_n]}{H_{RX}[k,f_n]}, \qquad (3)$$
$$f_n = 0,1,2,...,N-1; \qquad k = 0,2,4,...,K-2.$$

As in the case of pattern 1, the values of the C_H coefficients are used in two ways. In the first case, the $H_{RX}[k+1,f_n]$ subcarrier is corrected by the C_H correction value for the subcarrier in one preceding symbol:

$$\widehat{H}_{RX}[k+1,f_n] = H_{RX}[k+1,f_n] \cdot C_H[k,f_n]. \qquad (4)$$

In the second case, $H_{RX}[k+1,f_n]$ is corrected by the mean value of two neighbouring C_H coefficients: for the subcarrier in the preceding and following OFDM symbols (except for the $H_{RX}[K-1,f_n]$, for which only $C_H[K-2,f_n]$ is taken into account):

$$\widehat{H}_{RX}[k+1,f_n] = H_{RX}[k+1,f_n] \cdot \left(\frac{C_H[k,f_n]+C_H[k+2,f_n]}{2}\right).$$

This pattern of pilot tones allows the phase characteristics of the channel to be equalised in the subchannels for data transmission, based on the phase values for the subsequent pilot tones in the time domain. Phase distortions that can be corrected in this way are primarily caused by inter-symbol interference (ISI) and noise.

4. Replay channel simulation tests

The efficiency of OFDM signal correction using the proposed pilot tone patterns was tested using the Watermark simulator. It is a freely available benchmark for physical-layer schemes for underwater acoustic communications (van Walree *et al.*, 2017). Its core is a replay channel simulator driven by at-sea measurements of the time-varying impulse response. For testing OFDM signals, three of the communication channels available at Watermark were selected, represented by impulse responses measured in: Norway–Oslofjord (NOF1), Norway–Continental Shelf (NCS1), and Brest Commercial Harbor (BCH1). The impulse response of NOF1 reveals a few stable paths, as well as more clutter-like arrivals due to surface interactions. In the case of NCS1, there are no stable paths, thus it is a more challenging channel than NOF1. The impulse response of BCH1 is a mixture of stable and fluctuating arrivals, but with a larger number of distinct trailing paths (van Walree *et al.*, 2017). The basic parameters of the physical channels in which the measurements were carried out are presented in Table 2. The transmitter was bottom-mounted in Norway–Oslofjord (NOF1) and Norway–Continental Shelf (NCS1), and suspended in the water column in Brest Commercial Harbor (BCH1). The receiver was a bottom-mounted hydrophone (NOF1, NCS1) or a vertically suspended hydrophone array (BCH1) (van Walree *et al.*, 2017).

During the simulation, subsequent frames containing the synchronisation sequence and the OFDM signal of a duration of 2.5 s were sent one after another. The duration of each frame was equal to $T_{\text{OFDM}} + T_{\text{synch}} = 3.52$ s. In each frame, $N_i = 10$ kbits of information was sent in the case without pilot tones (the data transmission rate was equal to 2.84 kbps) and $N_i = 5$ kbits was sent in the case with pilot tones (the data transmission rate was equal to 1.42 kbps). One bit of information was represented by the phase of a single subcarrier in a single OFDM symbol. The bit error rate was calculated as BER $= N_e/N_i$, where N_e is the number of incorrectly detected bits in a single transmission frame.

Table 2. Watermark channels' parameters and sounding conditions (van Walree *et al.*, 2017).

Parameter	NOF1	NCS1	BCH1
Environment	Fjord	Shelf	Harbour
Range [m]	750	540	800
Water depth [m]	10	80	20
3 dB frequency band [kHz]	10–18	10–18	32.5–37.5
Delay coverage [ms]	128	32	102
Doppler coverage [Hz]	7.8	31.4	9.8
Type	SISO	SISO	SIMO

Tables 3–5 present the results of the simulation tests carried out. The best results were obtained for the BCH1 channel, which represents the harbour environment, and the transmission was carried out in the 32.5–37.5 kHz frequency band. The highest error rate was obtained in tests with the NCS1 channel, which represents the shelf environment.

In all three types of channel, the pilot tone correction pattern for the following OFDM symbols (pattern 2) gave a greater improvement in reliability than the correction pattern for subsequent subcarriers (pattern 1). In the case of NOF1, the advantage of pattern 2 is significant, but in the case of the NCS1 channel, it is not so clear. The lowest BER was achieved in the BCH1 channel, the highest one comes from the NCS1 channel.

In the case of the BCH1 channel, equalisation with pilot tones gave the greatest improvement, especially when using $k-1$ and $k+1$ pilot tones. While for small numbers data subcarriers (4, 8, or 16) it can be seen that pattern 2 is better, for 32 and 64 data subcarriers,

Table 3. OFDM transmission results for NOF1 Watermark channel.

Number of subcarriers	BER				
	No pilot tones	Pattern 1 one pilot tone	Pattern 1 two pilot tones	Pattern 2 one pilot tone	Pattern 2 two pilot tones
4	0.499	0.466	0.492	0.509	0.502
8	0.552	0.307	0.301	0.240	0.187
16	0.537	0.250	0.240	0.147	0.117
32	0.556	0.193	0.140	0.083	0.065
64	0.538	0.126	0.081	0.054	0.038

Table 4. OFDM transmission results for NCS1 Watermark channel.

Number of subcarriers	BER				
	No pilot tones	Pattern 1 one pilot tone	Pattern 1 two pilot tones	Pattern 2 one pilot tone	Pattern 2 two pilot tones
4	0.517	0.492	0.497	0.461	0.440
8	0.525	0.498	0.478	0.409	0.369
16	0.509	0.451	0.455	0.323	0.284
32	0.517	0.354	0.315	0.268	0.233
64	0.519	0.304	0.257	0.201	0.164

Table 5. OFDM transmission results for BCH1 Watermark channel.

Number of subcarriers	BER				
	No pilot tones	Pattern 1 one pilot tone	Pattern 1 two pilot tones	Pattern 2 one pilot tone	Pattern 2 two pilot tones
4	0.500	0.072	0.054	0.039	0.022
8	0.503	0.035	0.009	0.019	0.011
16	0.508	0.018	0.006	0.010	0.005
32	0.510	0.009	0.005	0.008	0.004
64	0.508	0.011	0.006	0.008	0.005

pattern 1 and pattern 2 gave similar results. In all types of channel, better results were obtained for both patterns when two adjacent pilots were used to calculate the correction coefficient. The higher the number of subcarriers, and therefore the longer the time-domain OFDM symbol, the greater the reduction of BER using the pilot tones.

5. Underwater experiment

The inland water OFDM communication tests were conducted on 5th May, 2017, in Wdzydze Lake on the northern edge of the Bory Tucholskie forest complex (53°58′31″N 17°54′19″E). The bottom of the lake falls steeply into the depths of the water. In the shore zone, it is lined with gravel-stony material, and in the deeper parts, covered with a layer of mud.

The water surface was calm during measurements. The weather was windless; it was not raining. Figure 3 shows the configuration of the experiment. The transmission stand was placed on the board of the boat. The boat was not anchored, and it drifted very slowly. Therefore, the Doppler effect had some impact on the transmitted signal, but to a much lesser extent than strong multipath propagation (Schmidt *et al.*, 2017). The receiving equipment was placed in a measuring container whose position was fixed. Transmission transducer was sunk to a depth h_{T_x} of 10 meters, regardless of the water depth of about 20–30 meters. The receiving transducer was sunk to a depth h_{R_x} of 4 meters at a constant water depth of 7 meters. The distance d between the transmission and receiving stands was 340 meters.

The OFDM signal was generated using the MATLAB platform. Conversion to an analogue signal was performed using a digital-to-analogue converter from an NI USB-6363 device. Next, the signal was amplified and transmitted to the water by an HTL-10 underwater telephone (Schmidt, 2016).

Prior to the measurement series, the sound speed profile was determined using a sound speed meter depending on the depth. The measured profile, and based

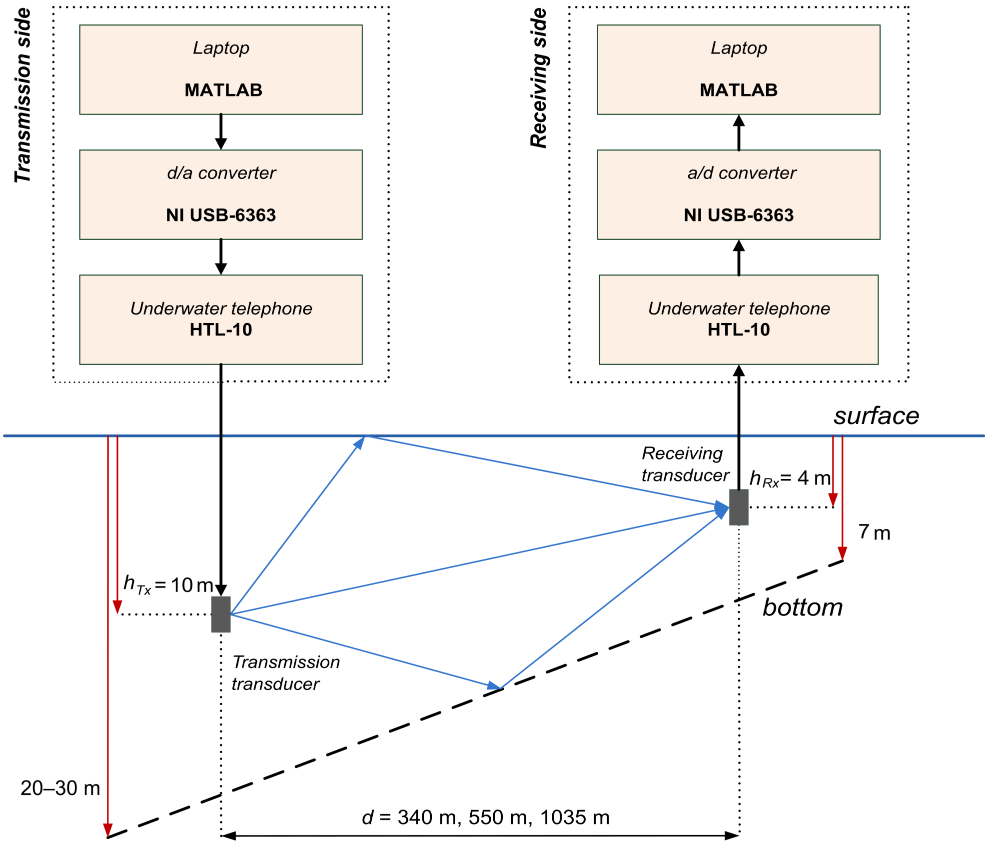

Fig. 3. Measuring system.

on this, the range of the communication system, was estimated by defining sound propagation paths, as shown in Fig. 4.

The data transmission tests were preceded by measurement of the channel impulse responses. On their basis, it was estimated that the delay spread was not greater than 10 ms, and the Doppler spread was less than 2 Hz (Schmidt *et al.*, 2017).

The communication tests were performed using the OFDM signal with different parameters (Table 1). Subsequent frames containing the synchronisation sequence and the OFDM signal of a duration of 2.5 s were sent one after another. The results are shown in Table 6.

Similarly to the simulation tests using Watermark channels, the bit error rate was calculated for a transmission of 10 kbits of information in the case without pilot tones. The duration of each frame was equal to $T_{\mathrm{OFDM}} + T_{\mathrm{synch}} = 3.52$ s, thus the data transmission rate was equal to 2.84 kbps in the case without pilot tones, and 1.42 kbps in the case with pilot tones. The bit error rate was calculated as BER = N_e/N_i, where

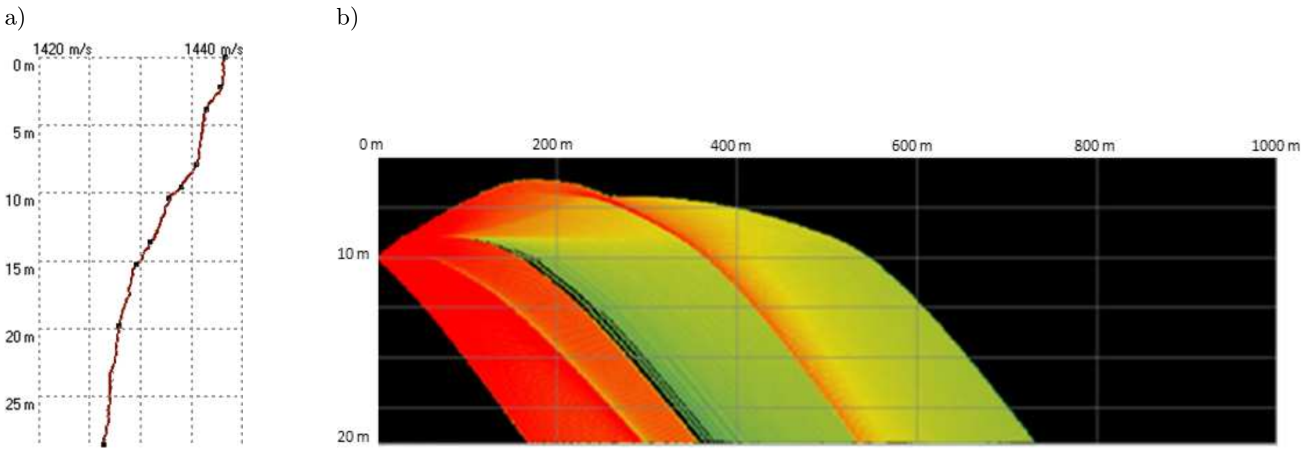

Fig. 4. Measured sound speed profile (a) and estimated range (b).

Table 6. OFDM transmission results during the inland water experiment.

Number of subcarriers	BER				
	No pilot tones	Pattern 1 one pilot tone	Pattern 1 two pilot tones	Pattern 2 one pilot tone	Pattern 2 two pilot tones
4	0.499	0.525	0.565	0.370	0.341
8	0.502	0.458	0.450	0.241	0.190
16	0.500	0.331	0.272	0.202	0.163
32	0.498	0.197	0.154	0.108	0.077
64	0.501	0.110	0.082	0.058	0.047

N_e is the number of incorrectly detected bits in a single transmission frame and N_i = 5 kbits and N_i = 10 kbits in the case with and without pilot tones, respectively.

It can be clearly seen that data transmission without channel correction cannot be performed. The use of pilot tones makes the detection of information in the receiver possible. The higher the number of subcarriers, and therefore the longer the OFDM symbol in the time domain, the greater the reduction of BER using the pilot tones.

The pilot tone correction pattern for the following OFDM symbols (pattern 2) resulted in about twice as much improvement in reliability as the correction pattern for subsequent subcarriers (pattern 1). In addition, better results were obtained for both patterns when two adjacent pilots were used to calculate the correction coefficient.

6. Conclusions

The underwater experiment, performed with the use of a laboratory model of an OFDM communication system, and simulation tests with the use of the Watermark simulator, have shown that reliable data transmission is not possible without the technique of equalising the influence of the channel on the spectrum of the transmitted signal. The pilot tones technique was applied according to two different patterns. The pilot tone correction pattern for the following OFDM symbols (pattern 2) gave a greater improvement in reliability than the correction pattern for subsequent subcarriers (pattern 1). This is probably due to the fact that in the case of all tested channels, the inter-symbol interference is a dominant distortion of the transmitted signal. All tested channels were characterised by strong multipath propagation and relatively low variability and influence of the Doppler effect on the transmitted signal. The correction according to pattern 1 does not minimise inter-symbol interference as well as pattern 2 does. Similar conclusions can be found in (Nissen, 2005).

Increasing the number of subcarriers, and thus extending the OFDM symbol in the time domain, improves the reliability of data transmission, provided that the pilot tones are used. This is probably due to the fact that the longer the symbol duration (and the longer cyclic prefix), the lower the probability of inter-symbol interference.

The bit error rate obtained during the underwater experiment is of the same order as the error rate obtained during the Watermark simulation in the fjord environment, channel NOF1. In the case of transmission on 64 subcarriers, a BER < 0.05 was obtained.

Reliability could be further improved by introducing redundancy, e.g. by means of forward error correction (FEC) coding. In this way, the BER could be reduced by at least one order of its value at the expense of transmission rate. In modern LTE radiocommunication systems using OFDM technique, FEC codes with an efficiency of 0.15 are used in particularly difficult propagation conditions (ETSI, 2016). In the case of a UAC system, it would mean a reduction of the transmission rate to about 200 bps, which would still be sufficient for most applications of underwater communication systems.

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