# MEASUREMENTS OF TRANSMISSION PROPERTIES OF ACOUSTIC COMMUNICATION CHANNELS[1]

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*Tough transmission properties of shallow water acoustic channels (SWAC) highly limit the use of underwater acoustic communication (UAC) systems. An adaptive matching of modulation and signaling schemes to instantaneous channel conditions is needed for reliable data communications. This creates, however, unique challenges for designers when compared to radio transmission systems. When communication system elements are in move, the accuracy of both the measurements of channel impulse responses and estimates of transmission characteristics is strongly limited, due to rapid variations of the channel performance. This paper describes communication tests of a model of the orthogonal frequency division multiplexing (OFDM) data transmission system. developed by the authors. The measurement procedures and signal processing algorithms were, first, tested in reverberant air-acoustic channels available in the laboratory, and, next, verified in natural conditions in a lake. The air acoustics trials prove to be effective and methodically correct.*

## INTRODUCTION

Inland water communication channels that are of interest to the authors, are mostly classified as shallow water acoustic channels (SWAC). Due to the large variability of their properties and strongly varying instantaneous conditions, there is a need for adaptive matching of the UAC systems signaling to transmission properties of the channel. This requires a knowledge of instantaneous channel characteristics in terms of specific parameters of stochastic models describing channel time-variability. These parameters, including the delay spread, coherence time and coherence bandwidth, are estimated on the basis of quasi-continuous measurements of the channel impulse response.

The adaptive OFDM technique is being implemented in a laboratory model of acoustic data transmission system, designed at the Department of Marine Electronics Systems, Faculty of Electronics Engineering, Telecommunications, and Computer Science, Gdansk University

[1] supported by grant from the Ministry of Science and Higher Education, no 4706/B/T02/2011/40

of Technology. The motivation is to achieve reliable data communication in shallow inland waters, with the best possible performance, self-adapting to local, instantaneous conditions [1,2].

While the research in radio communications is mostly based on simulations using established models, the research in underwater acoustic communications is mostly based on sea trials, expensive, time-consuming, and weather dependent. For a time gain and lower costs, introductory tests of acoustic communication can be performed in the air. Channel measurements and communication tests performed in winter period in such friendly conditions can brought much experience to the authors, enriching profitably their design intuition.

This paper describes communication tests conducted with the use of a laboratory model of an OFDM data transmission system in both static and moving configurations of a receiver, first, in reverberant air-acoustic channels and, second, in a shallow lake. The impulse responses were measured using the correlation method based on transmission of pseudorandom maximum length sequence (MLS) signals. The dynamics of estimated channel transmission parameters was examined, and a procedure was developed and tested by the authors of matching the UAC system signaling parameters to varying channel conditions. The results allow for a discussion of relationships between the channel time-variability and limit values of the data transmission rate.

## 1. SEARCH FOR TRANSMISSION PARAMETERS METRICS

***Impulse response measurements*** are carried out using MLS signals. In order to estimate the channel characteristics with sufficient resolution, the channel needs to be sounded as often as necessary. [3,4].

It is desirable, that the impulse response was locally stationary throughout the duration of a single MLS sequence. Hence, the shorter the measurement sequence, the smaller is the possible change of the measured impulse response during a single sequence. At the same time, however, the sequence should be long enough to cover the entire impulse response of multipath channel, otherwise temporal aliasing can appear as source of a significant measurement error [5].

***Flexible channel modelling*** is required for the adaptation of OFDM technique to ultrasound underwater communication. The most known and used in radio communications is the model based on the assumption of wide sense stationarity (WSS) of channel statistics and uncorrelated scattering (US) of multipath components achieving the system receiver [2-4,6]. Statistical parameters estimated from current impulse response and the channel model adopted are essential for OFDM signal parameters design [7]. The measured characteristics of the channel determine the physical layer parameters, such as the symbol duration, guard time duration and subcarriers spacing.

***Specifying the metrics of transmission parameters***, such as delay spread, coherence time and coherence bandwidth, for acoustic communication systems is needed, similar to radio communication systems, where the detailed rules for designing OFDM signals are known [1,7]. The acoustic channels being much different from the wireless ones, they do not meet the usual assumptions of quasi-stationary statistics used in radio system design.

The time spread of the acoustic channel is being characterized by the (commonly used in radio system analysis), root-mean-square value and maximum value of time-delay relative to the strongest component, calculated from the multipath intensity profile [7]. The coherence bandwidth and the coherence time are measured as the width of frequency correlation function and time correlation function, respectively, on several threshold levels. Examples of these characteristics are shown at Fig. 1. For the multipath intensity profile, maximum delay spread $\tau_M$ is marked as the time between the first and last received multipath component, at the threshold level of 10dB below the level of strongest component. Coherence bandwidth $B_{c0.5}$ and coherence time $T_{c0.5}$ are presented as the width of frequency correlation function and time correlation function, respectively, at threshold level of 0.5 of maximal value.

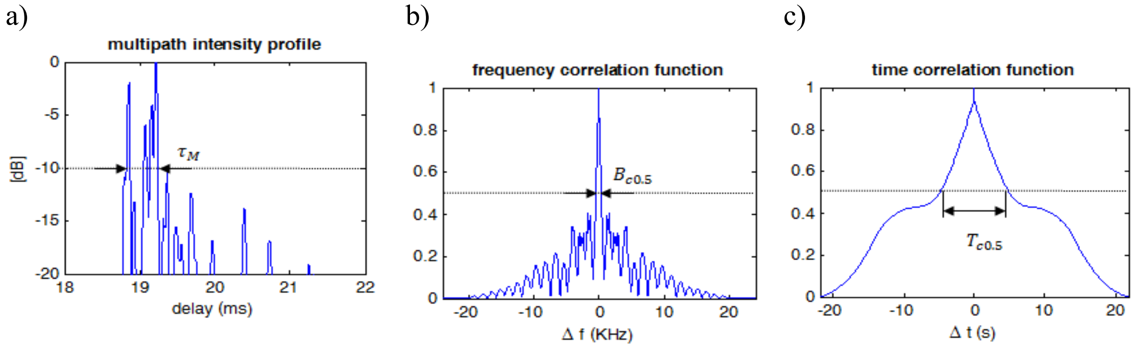


Fig.1. Example transmission characteristics of acoustic channel;
multipath intensity profile (a), frequency correlation function (b) and time correlation function (c).

## 2. LABORATORY TRIALS

For a time gain and lower costs, introductory channel impulse response measurement, transmission properties estimation and acoustic communication were performed by the authors in the air, in the Department premises. Laboratory trials allow to test measurement procedures and signal processing algorithms, implemented in the laboratory model of underwater communication system.

First, the acoustic channel was modelled at the roof of a building, with a few reflections, but strong environmental noise caused by the wind. Next, the reverberant acoustic channel was modelled in a long corridor 2.5 m wide and 2.5 m high. The measurements were performed over a distance of up to 6.5 meters that corresponds to almost 30 meters in water.

Standard loudspeaker and microphone were electroacoustic terminations replacing the underwater loudspeaker and hydrophone of the laboratory model of the OFDM data transmission system comprising two acoustic amplifiers, and two notebook computers with external USB sound cards. Microphone was fixed to a rope through a pulley system, moving with a speed of 40 cm/s, corresponding to about 1.7 m/s in water.

***Transmission characteristics*** of acoustic channels were estimated based on measured impulse responses, collected with sufficient resolution. MLS signals of different order, from L=8 to 15 were used, repeated up to 256 times one after the other. All signals were created and recorded at 96 ksamples/second

The measured impulse responses and scattering functions are show in Figs. 2, 3 and 4 for three realizations of acoustic reverberant channel on the roof and in the corridor. In the first and second case the communication system was immobile. In the third case the microphone was moving in a uniform manner at a speed of about 40 cm/s. Table 1 presents the results of the transmission parameter analysis.

The delay spread maximum $\tau_M$ and rms $\tau_{rms}$ values were measured at -10 dB threshold level of the multipath intensity profile [7]. The coherence bandwidth $B_c$ was measured as the width of the frequency correlation function at several threshold levels, i.e. 0.9, 0.7 and 0.5 of the maximum value. Similarly, the coherence time $T_c$ was measured at the same threshold levels of the time correlation function. In the case of narrowband radio channels, the Doppler spread is usually defined as the width of the Doppler power spectrum function [7]. In the case of broadband acoustic signals, the Doppler shift differs significantly for the upper and lower frequency limit of the bandwidth. The impact of the transmission system elements (or reflecting surface) movement has to be analyzed here in the time domain, as a time compression or expansion of the signal. In the first approach the authors assumed that the variability of the channel can be characterized by mere coherence time. It turns out that new metrics are necessary, characterizing signal changes by proper time compression/expansion coefficients instead of usually used Doppler frequency shifts.

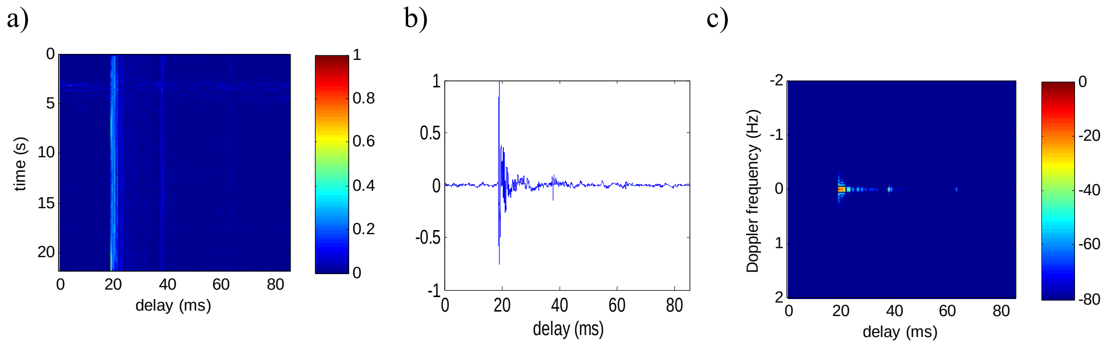


Fig.2. Static acoustic channel – the roof, distance 6.5 m;
impulse responses (a), single impulse response (b), and scattering function (c).

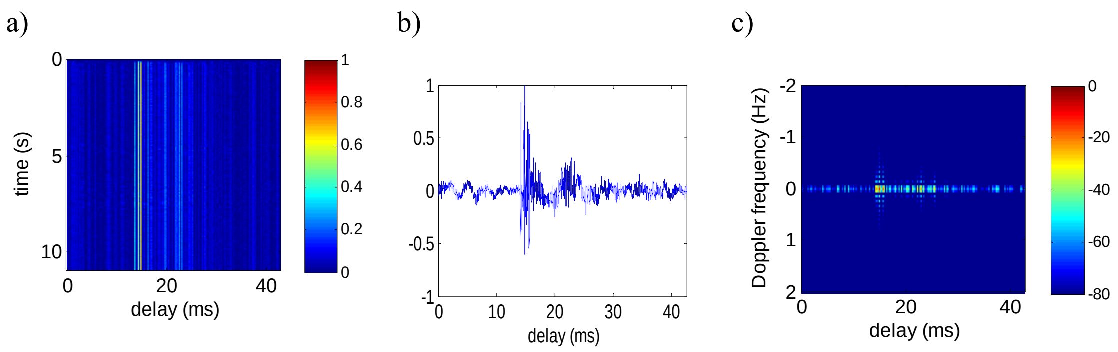


Fig.3. Static acoustic reverberant channel, distance 4.5 m;
impulse responses (a), single impulse response (b), and scattering function (c).

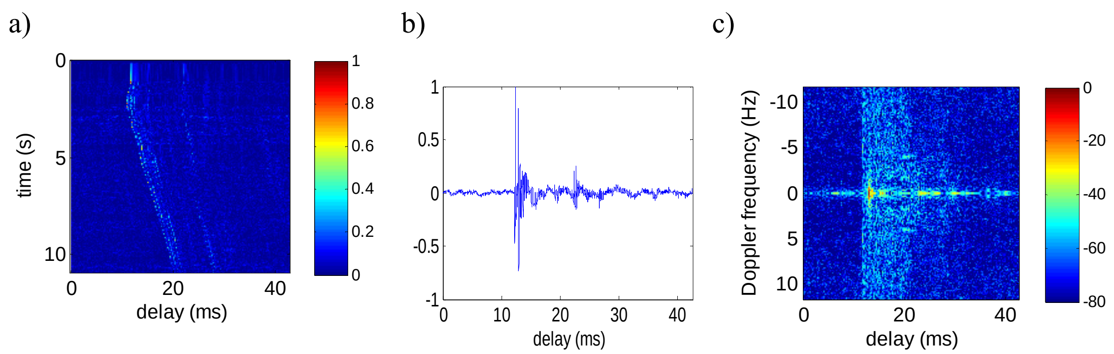


Fig.4. Mobile acoustic reverberant channel, distance from 3.7 to 6.5 m;
impulse responses (a), single impulse response (b), and scattering function (c).

***Transmission tests*** were carried out in air for different configurations of the OFDM signal parameters. The bandwidth of the communication system was 3 kHz, with the centre frequency of 5 kHz. The subcarrier spacing was varied from 23.44 Hz to 2.93 Hz. A cyclic prefix was used of a length equal to 1/5 of the OFDM symbol length. Binary data, coded with PSK digital modulation scheme, were transmitted in each of the subchannels. Every second subcarrier was used as a pilot tone for simple equalization of the neighbouring data tones. During each of the transmission tests, the number of the subchannels that met a given requirement on the error rate, was measured, hence the communication system throughput could be calculated. The results are shown in Table 2. The number $N_{OFDM}$ of the subchannels meeting a given BER requirement is shown as the percentage of all data subchannels.

Tab.1. Transmission parameters estimated on the basis of impulse responses of Figs. 2, 3, and 4.

| Channel | delay [ms] | | coherence bandwidth [Hz] | | | coherence time [s] | | |
|---|---|---|---|---|---|---|---|---|
| | $\tau_M$ | $\tau_{rms}$ | $B_{c0.5}$ | $B_{c0.7}$ | $B_{c0.9}$ | $T_{c0.5}$ | $T_{c0.7}$ | $T_{c0.9}$ |
| static – roof | 0.41 | 0.38 | 926 | 562 | 176 | 9.8 | 4.5 | 0.7 |
| static – corridor | 1.4 | 0.5 | 387 | 258 | 47 | 10 | 8 | 1 |
| mobile – corridor | 30 | 10 | 11.72 | 11.72 | 0 | 2 | 0.34 | 0 |

Tab.2. Results of OFDM communication tests in channels of Figs. 3 and 4.

| | | Static channel (Fig. 3) | | | | Mobile channel (Fig. 4) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | BER≤$10^{-1}$ | | BER≤$10^{-3}$ | | BER≤$10^{-1}$ | | BER≤$10^{-3}$ | |
| $B_{OFDM}$ [Hz] | $T_{OFDM}$ [s] | data rate [bit/s] | $N_{OFDM}$ [%] | data rate [bit/s] | $N_{OFDM}$ [%] | data rate [bit/s] | $N_{OFDM}$ [%] | data rate [bit/s] | $N_{OFDM}$ [%] |
| 23.44 | 0.05 | 323 | 31 | 32 | 3.0 | 0 | 0 | 0 | 0 |
| 11.72 | 0.10 | 539 | 47 | 35 | 3.0 | 48 | 5.5 | 6 | 0.8 |
| 5.86 | 0.20 | 798 | 67 | 56 | 4.5 | 121 | 11.7 | 93 | 9.0 |
| 2.93 | 0.40 | 908 | 74 | 31 | 2.5 | 73 | 6.5 | 44 | 3.9 |

As one could expect, in the static reverberant channel, narrowing of a subchannel bandwidth determined higher data rate with a given acceptable BER. Longer OFDM symbol made the signal more immune to intersymbol interferences. In the case of a mobile system, the transmission failed for the subchannel bandwidth greater than 11.72 Hz, that corresponds to the coherence bandwidth calculated on the basis of the frequency correlation function at the threshold level of 0.7. For the subchannel bandwidth of 5.86 Hz, a significant increase of the bit rate was observed. However further narrowing of the subcarrier spacing led to a decrease of the relative number of acceptable subchannels. The highest transmission rate was achieved for the symbol length of 0.2 s, that indicates that the symbol length should be significantly lower than the coherence time determined from the time correlation function at the threshold level of 0.7. Thus, the signal design recommendations for the measured reverberant acoustic channel can be formulated as:

$$B_{c0.7} > B_{OFDM} \quad (1)$$

$$T_{c0.7} \ll T_{OFDM} < \tau_{rms} \quad (2)$$

where: $B_{OFDM}$ and $T_{OFDM}$ are the OFDM subchannel bandwidth and symbol duration, respectively; $B_{c0.7}$ and $T_{c0.7}$ are the coherence bandwidth and coherence time calculated as the width of the corresponding correlation function at the level of 0.7 of maximum value; $\tau_{rms}$ is the root mean square value of the delay spread.

## 3. UNDERWATER COMMUNICATION TESTS

Underwater experiments were carried out in a lake. A hydrophone and hydroacoustic speaker were used with appropriate amplifiers, together with the same notebook computers and external sound cards with sampling frequency of 96 ksamples/second. The communication software was developed and extensively tested during laboratory air communication tests. The underwater channel was ca. 4 m deep, and experiments were performed at distances from 1 to 30 m. The speaker was placed 1 or 2 m below the surface and the hydrophone was placed 0.5, 1 or 2 m below the surface. In mobile scenarios, the hydrophone was moving slowly with the velocity of 15 cm/s

***Transmission characteristics*** of underwater channel were measured using the same MLS signals, as in the case of laboratory trials. The measured impulse responses and scattering functions are show in Figs. 5 and 6 for two realizations of underwater communications: a static one and one with a slowly moving receiver.

a) b) c)

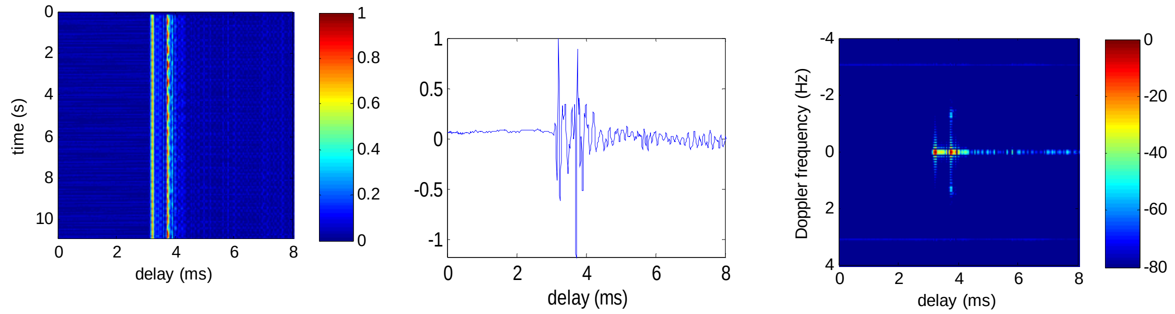


Fig.5. Static underwater channel, distance 4 m;
impulse responses (a), single impulse response (b), and scattering function (c).

a) b) c)

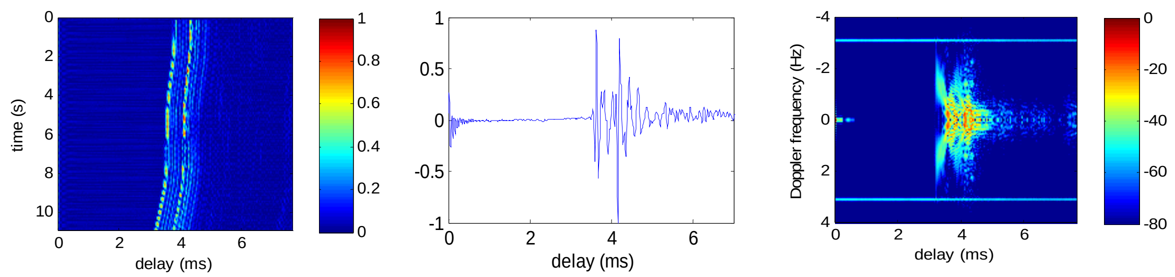


Fig.6. Mobile underwater channel, distance from 5.4 to 4 m;
impulse responses (a), single impulse response (b), and scattering function (c).

Table 3 presents results of the transmission parameter analysis for the two cases. The maximum and rms values of the delay spread were measured at the -10 dB threshold level of the multipath intensity profile. The coherence bandwidth and the coherence time were measured as the width of the corresponding functions at the threshold levels of: 0.9, 0.7 and 0.5.

***Transmission tests*** were performed immediately afterwards, in the same conditions. Similarly as in the case of the in-air laboratory experiments, the bandwidth of the communication system was 3 kHz, with the centre frequency of 5 kHz.

Three configurations of the OFDM signal parameters were examined, with the symbol duration values around the coherence time at threshold level 0.7 of the mobile channel (Table 3). Thus the subcarrier spacing was set, subsequently, at 23.44 Hz, 11.72 Hz and 5.86 Hz. The same length of the cyclic prefix was used as in the air, equalling 1/5 of the OFDM symbol. The transmitted OFDM frames consisted of a synchronization sequence 1.36 s long, and 64 data symbols, each lasting, respectively, 3.2 s, 6.5 s, and 13.1 s. Similarly as in the air acoustics experiment, binary data coded with PSK digital modulation scheme, were transmitted in each of the OFDM subchannels. Every second subcarrier was used as a pilot tone.

Tab.3. Transmission parameters estimated on the basis of impulse responses of Fig. 5 and Fig. 6.

| Channel | delay [s] | | coherence bandwidth [Hz] | | | coherence time [s] | | |
|---|---|---|---|---|---|---|---|---|
| | $\tau_M$ | $\tau_{rms}$ | $B_{c0.5}$ | $B_{c0.7}$ | $B_{c0.9}$ | $T_{c0.5}$ | $T_{c0.7}$ | $T_{c0.9}$ |
| static | 0.5 | 0.4 | 632 | 492 | 257.8 | 0.71 | 0.12 | 0.08 |
| mobile | 4.4 | 1.5 | 351 | 70 | 46.9 | 0.17 | 0.09 | 0.00 |

During each of the transmission tests, the number of the subchannels that met the requirement for a given bit error rate, was measured. On this basis the communication system throughput was calculated. The results are shown in Table 4.

Tab.4. Results of OFDM communication tests in the channels of Fig. 5 and 6.

| | | Static channel (Fig. 5) | | | | Mobile channel (Fig. 6) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | BER ≤ 10-1 | | BER ≤10-3 | | BER ≤ 10-1 | | BER ≤10-3 | |
| $B_{OFDM}$ [Hz] | $T_{OFDM}$ [s] | data rate [bit/s] | $N_{OFDM}$ [%] | data rate [bit/s] | $N_{OFDM}$ [%] | data rate [bit/s] | $N_{OFDM}$ [%] | data rate [bit/s] | $N_{OFDM}$ [%] |
| 23.44 | 0.05 | 372 | 42 | 13 | 1.5 | 303 | 34 | 13 | 0.4 |
| 11.72 | 0.1 | 582 | 56 | 16 | 1.5 | 347 | 67 | 16 | 0.8 |
| 5.86 | 0.2 | 880 | 77 | 22 | 2.0 | 615 | 54 | 0 | 0.0 |

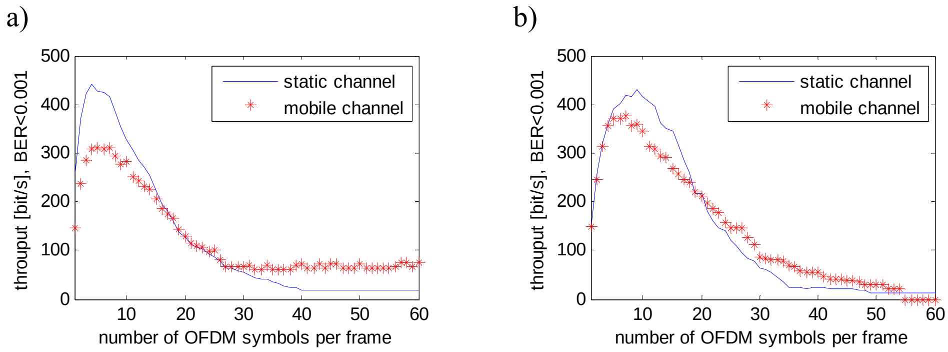


Fig.7. Evolution of OFDM communications system throughput with the number of OFDM symbols per frame; BER≤$10^{-3}$; acoustic reverberant channel (a) and underwater channel (b).

As in the case of the in-air tests of reverberant channel, the static trial showed, that a narrowing of the OFDM subcarrier spacing enables to achieve a higher data rate at the given acceptable BER. In the case of the mobile underwater channel the test transmission of 64 OFDM symbols with the required BER≤10-3 failed for the duration of the OFDM symbol equal 0.2 s, greater than the channel coherence time measured at 0.7 of the maximum value of the correlation function (0.09 s). There were, however, successful transmissions of frames containing less than 64 symbols. The number of the OFDM subchannels satisfying given BER assumptions was rapidly declining with time. Thus, to achieve a transmission of the best reliability, a transmitted frame should include the smallest possible number of OFDM symbols. On the other hand, the synchronization sequence of 1.36 s significantly affects the throughput of the system. Figure 7 shows the dependence of the throughput on the number of symbols in a single OFDM frame.

## 4. CONCLUSIONS

The implementation of self-adapting, reliable data communication schemes requires ad-hoc design methods to be developed, needing a multitude of in-the-field tests. The air acoustics in-the-laboratory trials prove to be effective and methodically correct, both from the technical and economy point of view. When corrected for the difference of sound velocities, the geometry and motion conditions of signal transmission, in both air and underwater acoustic channels, turned out to be quite similar. Hence an efficient modelling and verification of communication tests in highly reverberant conditions are possible in the laboratory.

The impulse response measurements and communication tests were conducted with the use of a laboratory model of a low frequency, broadband OFDM data transmission system, first, in reverberant air acoustic channels and, next, in an inland shallow water ultrasonic channel. The laboratory trials have brought to the authors much experience in measuring acoustic channels, testing transmission signal design procedures and processing algorithms for underwater communications applications. For designing the signal physical layer recommendations, an appropriate metric of the coherence time of the channel is verified by the authors to be the width of time correlation function at the threshold level of 0.7 of its maximum value. Also, the best ratio of a synchronization sequence duration to the duration of data symbols was estimated. The results will be subject of further verification in field experiments.

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