Long-Range Underwater Acoustic Navigation and Communication System

Aleksandr Rodionov[1], Petr Unru[2*], Aleksandr Golov[3]

[1]Institute of Marine Technology Problems FEB RAS, Vladivostok, Russia
[2]Far Eastern Federal University, Vladivostok, Russia
[3]V.I. Il'ichev Pacific Oceanological Institute FEB RAS, Vladivostok, Russia
[*]Corresponding Author: Email: unrupp@gmail.com

Abstract

The paper presents a performance analysis of a digital underwater acoustic communication system for operating distances above 300 km in 300-500 Hz bandwidth. Estimating the system's performance relies on the underwater acoustic channel model involving a rapid transition from shelf zone to deep-sea consisting of ray patterns and channel impulse responses. Reverberation in such conditions of 200-600 ms imposes specific design requirements to an efficient digital system of commands and data transmission in such a narrow band. The bitrate of 20 bit/s was achieved for stated distances under severe multipathing.

Keywords: underwater acoustics, underwater acoustic navigation, communication systems, long-haul underwater communication

Introduction

Autonomous underwater robotic complexes gain constantly increasing popularity as well as unmanned aerial systems. An inherent part of such underwater complexes is a communication and navigation system that provides positioning with the necessary accuracy and throughput sufficient for transmitting control instructions. In the last decade, the World Ocean's research and exploration depend on autonomous unmanned vehicles controlled using underwater acoustic systems. The use and active development of digital underwater acoustic communication for these purposes are based on the fact that this is the only means of communicating underwater media on substantial distances. Optical and wireless electromagnetic technologies cannot compete with underwater acoustic ones on distances above hundreds of meters.

When organizing long-haul and extra-long-haul underwater acoustic communication (more than 300 km) with autonomous unmanned underwater vehicles, it is necessary to understand that only simplex communication is possible unless vehicles can carry bulky transmitters with an output power of at least units of kW. It is also required to deal with many challenges like matching the low-frequency equipment with a capacitive load of the antenna, the need for the low peak-to-average ratio of the signals used, multipathing with high reverberation time appeared in the reception points of long-haul signal paths, Doppler frequency spreads of certain multipath components combined with narrow bandwidth. In such initial conditions, it is necessary to use correct models of the designed communication system considering factors influencing the total performance.

Proposed system

As the required distance of communication for long-range positioning and unilateral connection with small underwater vehicles is at least 300 km, hundreds of Hz's bandwidth must be chosen based on the well-known relations [1]. The further methods, calculations, and modeling consider the bandwidth of 300-500 Hz, which corresponds to the underwater acoustic communication system's optimal frequency on distances of about 500 km. An example of sound pressure distribution and channel impulse responses (CIR) when transmitting a 400 Hz signal alongside a 300-400 km channel are presented in Fig. 1-3. This band also corresponds to the reactance factor of existing low-frequency piezoceramic transducers [2].

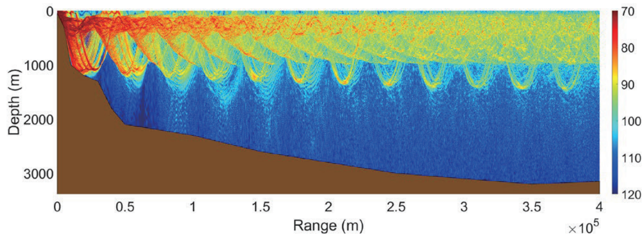

Fig.1 Sound pressure distribution alongside the 400 km channel for 400 Hz signal.

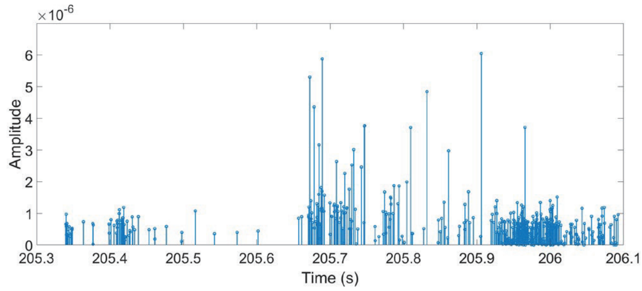

Fig. 2 Channel impulse response at the reception point 300 km away from the transmitter.

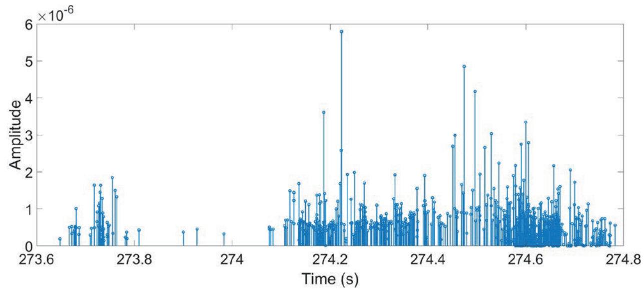

Fig. 3 Channel impulse response at the reception point 400 km away from the transmitter.

Modern underwater acoustic communication means can be divided into the following categories according to the signal processing method: with high spectral efficiency (from 1 to 4 bit/s/Hz), based on parallel frequency division of

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information-bearing symbols (OFDM) and M-QAM methods; with average spectral efficiency (from 0.1 to 1 bit/s/Hz) based on sequential frequency division (S2C) [3,4]; and with low spectral efficiency (lower than 0.1 bit/s/Hz) based on DSSS methods [5]. Theoretically, the system's stated spectral efficiency allows designing relatively high-speed underwater acoustic channels for data transmission (up to tens of kbit/s). However, such performance is achievable when the communication channel parameters are stable and the receiving-transmitting system went through a complex tuning process. In natural conditions, the underwater acoustic communication system's performance heavily depends on several factors influencing at the same time: MAC-protocol used, reverberation time in the channel, current signal-to-noise ratio, presence or absence of impulse noises, motion speed of receiver, transmitter, and so on. Such a variety of factors result in the real throughput of these systems from hundreds of bit/s to units of kbit/s in frequency bands used to communicate on distance up to several kilometers.

This study's main objective is to develop and test the algorithms of signal processing and digital modulation tolerant to the combination of mentioned parameters when maximizing data throughput. Thus, it is necessary to solve the problem of implementing algorithms capable of operation without regular channel state estimation and equalization and multiple transmission of pilot signals. It is especially vital for extra-long-haul underwater acoustic communication systems with signal propagation time of 200-300 seconds with the constant motion of transmitting and receiving objects to save time resources of the channel and increasing the total throughput.

At the same time, the channel reverberation time, which varies in a wide range, must have a minimal impact on the data throughput of the system. The underwater acoustic communication system must also be sustainable to Doppler frequency spreads and provide adaptability for simple algorithms of impulse noise suppression in the receiving paths and non-coherent reception due to severe conditions of non-stationary channels.

The use of OFDM, which is popular in terrestrial radio protocols (Wi-Fi, DVB-T, WiMAX, 4G), allows increasing the throughput substantially by dividing the whole bandwidth into orthogonal subchannels to transmit data using high-rank M-QAM with time guard intervals. This approach gained popularity in scientific activities in underwater acoustic communication, but its applicability in commercial systems is restricted [6]. The non-stationarity of the underwater acoustic channel leads to orthogonality distortion of the OFDM frequency channels. In general, this method has many problems, which are not yet solved [7]

Such a high dispersion of rays time of arrival (up to 1000 ms) makes use of classic methods of manipulation with sequential symbol data transmission (ASK, FSK, PSK) practically impossible considering the non-stationarity of the underwater acoustic channel. Such an approach coupled with time guard intervals provides a data throughput of units of bit/s for taken bandwidth of 200 Hz.

OFDM's implementation allows reaching spectral efficiency of bit/s/Hz units, resulting in an achievable total data rate of hundreds of bit/s. It is also necessary to consider the difficulties of creating a powerful amplifier and matching the antenna's capacitance load. This paper presents a method of sequential N multifrequency impulse data transmission with cyclic repetition of similar frequencies through N-1 frequency channel with Differential Phase (DBPSK) or amplitude shift keying (ASK) of impulses.

$$s_{tx}(t) = \sum_{i=1}^{N} D_i \cdot sin\left(2\pi\left\{t - \frac{2i}{\Delta f}\right\}\left[f_0 + \Delta f \cdot i\right]\right), \quad (1)$$

where $D_i = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$ is an information symbol in the i^{th} channel with ASK used for $D_i = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$ and DBPSK.

This method provides a stable signal envelope and high potential sustainability of reverberation effects and non-stationarity of the multipath underwater acoustic channel. In this case, the following expression connecting supposed channel reverberation time τ_E and length of information symbols and their number is fair.

$$\tau_E + \tau = N \cdot \tau\,, \quad (2)$$

where $\tau = 2 / \Delta f$ is an impulse length in one frequency channel, Δf is a channel bandwidth. Achievable data throughput for the proposed method can be defined as $f_b = N / (\tau_E + \tau) = 1/\tau = \Delta F_a / 2N = \Delta f / 2$. By solving $\Delta f^2 + 2 \cdot \Delta f / \tau_E - 2 \cdot \Delta F_a / \tau_E = 0$, we can obtain

$$N \approx \sqrt{0.5 \cdot \Delta F_a \cdot \tau_E}\,. \quad (3)$$

It is possible to estimate the necessary number of channels N of parallel processing and data throughput f_b for stated antenna bandwidth ΔF_a and the supposed value of channel reverberation time τ_E.

Computed data (Table 1) show the possibility of designing an underwater acoustic communication system working in the band of 300-500 Hz with a data rate acceptable for telemetry and navigation data transmission for AUV.

TABLE I
DATA RATE f_b, NUMBER OF CHANNELS N DEPENDING ON τ_E

τ_E	f_b	N
100 ms	33 bit/s	3
250 ms	20 bit/s	5
500 ms	14 bit/s	7
800 ms	11 bit/s	9
1 000 ms	10 bit/s	10
4 000 ms	5 bit/s	20

Such a solution can be considered as a particular case of the OFDM. The difference between them is that impulses of

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different frequency channels are not summarized in one complex symbol but are allocated in the time domain. It causes lower data rates and a lesser number of processing channels. In addition, a series of impulses of different frequencies is more sustainable to non-linear distortions of the amplifiers compared to OFDM. Increasing throughput is possible by adding channels N or decreasing Δf . It results in increasing the duration of impulses and their mutual overlapping in the time domain. Summing up of partially overlapped impulses of different frequencies in the time domain leads to the appearance of complex signal patterns. In that case, it is necessary to estimate the enlargement of the signal peak power depending on the relative position of impulses of different frequencies. The further numerical experiments were conducted for the particular case described by the above-mentioned expressions.

Numerical modeling

Based on previously conducted natural experiments on estimating the CIR of 300 km length underwater acoustic channels, the reverberation in underwater acoustic channels can be equal to 250 ms when the five-channel mode is used with data rate $f_b = 20$ bit/s.

CIR with multiple multipath peaks of high and low amplitude with low channel coherence time can result in a situation when the modulus of a correlation coefficient between neighboring symbols of one channel is dropped in magnitude significantly. That challenges the applicability of differential shift keying systems (DBPSK), with no chances of successful implementation of coherent reception and initial channel state estimation. An ASK mode of modulation of symbols of different frequencies in the numerical model allows performing a non-coherent reception of each symbol independently.

The received in the given bandwidth signal $s_{rx}(t)$ is processed by the quadrature filter on the predetermined i^{th} channel frequency using lowpass filters of high order with cut-off frequency $f_{cut} = f_b$. In that case, the key role is played by the level of interchannel interference $S/\Sigma I_i$, which is determined by the order of quadrature filters (Fig. 4).

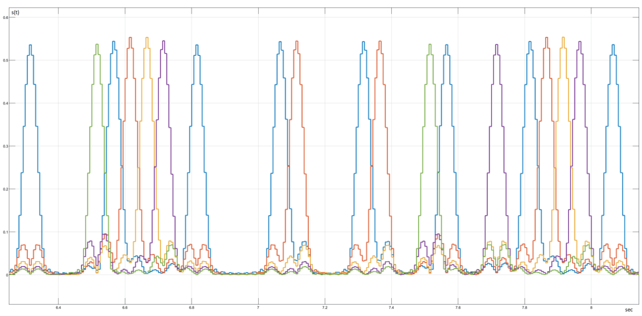

Fig. 4 Demodulated original vector ASK signal on the output of five quadrature filters with a data rate of 20 bit/s, level of $S/\Sigma Ii$ is 18 dB.

The interchannel interference level for the computational model does not exceed -18 dB when digital lowpass filters of a high order are used.

The chosen ray model of the channel with CIR can be described by the expression:

$$h(t) = 1 + 1e^{-j\omega \cdot 0.075} + 0.7e^{-j\omega * 0.1} + 0.5e^{-j\omega * 0.219} \tag{4}$$

In such a model, the signal formed by five frequency channels with a time guard interval of 250 ms allows to effectively accumulate multipathing in each channel within the limits of the stated guard interval (Fig. 5).

This signal transmission method allows implementing a multipath rays energy accumulation principle by integrating the signal within each frequency channel on symbol and guard interval duration. This operation is followed by threshold detection, like for ASK signals. If guard interval duration is chosen properly, the receiver's error probability can be determined as the relation between the summed power of all multipath components and combined noise magnitude and power of all interchannel interference when using ASK in a non-stationary multipath channel.

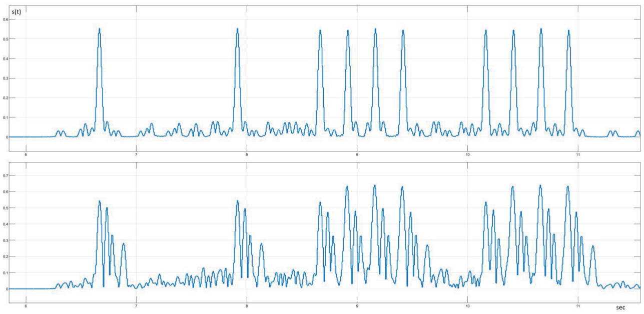

Fig. 5 Demodulated original signal of the third frequency channel and the same signal convoluted with the four-beam CIR.

Conclusion

The paper presents an approach to establishing an extra-long-haul underwater acoustic communication channel with strongly pronounced multipathing. The detailed description of the system proposed is supplemented with numerical modeling results, which demonstrate data rates for different parameters on the given distance (300 km). In a non-stationary multipath channel, if guard interval duration is chosen properly, the receiver's error probability can be determined as the relation between all multipath components' summed power and combined noise magnitude and power of all interchannel interference when using amplitude shift keying.

Acknowledgments

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