Modelling of a hydroacoustic modem for underwater communications

D A Tokmachev¹, A G Chensky¹, N S Zolotarev¹, A S Poletaev¹

¹ Irkutsk National Research Technical University, 83, Lermontov Street, Irkutsk, 664074, Russia.

E-mail: skb@istu.edu

Abstract. The paper discusses results of designing of an underwater communication device. The MSK modulation type is more preferable as it provides with narrow spectrum density of signals. The article describes a simulation program that allows one to model signal distortions and choose the best-fit method of detection. Three demodulation algorithms are tested. Simulation of signal propagating in underwater medium showed that the most effective is cross correlation detecting for which bit error rate was $5 \cdot 10^{-4}$ at signal-to-noise ratio of 6 dB. Signal distortions were modelled with additive white noise, phase drift and superimposed re-reflections. For a piezoceramic antenna with a resonant frequency of 55 kHz and 6 kHz bandpass, the transmission frequencies of “0” and “1” are defined as 54 kHz and 56 kHz respectively, bitrate is 4000 bauds. During experimental testing in conditions of a natural reservoir all electronic devices demonstrated stability, the maximum range of reliable transmitting was 250 m.

1. Introduction

Modern underwater research makes the most out of different unmanned vehicles. This great variety of devices includes remotely operated underwater vehicles (ROVs), autonomous underwater vehicles (AUVs), autonomous bottom stations and buoys, and surface vessels with hydroacoustic equipment onboard. A wireless system of information transmission is required for data exchange between a research vessel and the underwater vehicle. In addition, there is a very relevant problem of communication between divers and the head of diving operations on the surface. Conventional signs traditionally used by divers have many disadvantages. Among them the most significant are low efficiency, a high probability of missing the transmitted command due to adverse conditions in the aquatic environment. There are also wireline telephone systems for industrial deep-sea divers. Such communication systems, however, have concomitant drawbacks which limit their scope of application. The most significant is that a telephone cable limits the freedom of movement of the diver and increases a risk of disconnection from the diver [1].

The main problem of wireless underwater communications via electromagnetic waves with frequencies traditionally used in radio technical systems is that the radiowaves are greatly attenuated when passing through conductive medium, soil, rocks, water column. Typically applied in navy radio navigation, 16-24 kHz bandwidth provides with extremely low data transfer rate (100 – 200 bauds) and requires the use of large radiation powers and antennas with sizes bigger than a hundred meters [2]. In contrast, acoustic waves in water have low attenuation and can propagate over long distances. Therefore, the use of a hydroacoustic communication channel is one of the most effective ways of transmitting...
However, for the effective use of the hydroacoustic communication channel, it is necessary to solve a number of problems. For example, minimizing of impact of natural and man-made noise in water, multipath signal propagation fading, non-uniform frequency-dependent signal absorption, etc. All these factors affect negatively the communication range, data transfer rate, and noise immunity of the transmit channel [4]. There is a complex of technical solutions for it and one of them is applying an effective type of signal modulation which is most proper for underwater medium [5].

2. Choosing of a modulation type
In our system of hydroacoustic communication for divers and underwater technical equipment, we selected the frequency shift keying (FSK) method that is the least sensitive to phase drift of a signal. The phase instability is caused with multiple re-reflections and multipath propagation. High communication range and data bit rate can be also reached with the use of more complex modulation type – OFDM (orthogonal frequency-division multiplexing), but it requires a wide bandwidth of a transceiving path.

There is no sense to use simple FSK with breaking phase because this arise a number of strays frequencies and also lead to signal spectrum broadening. When phase shifts are absent while modulation symbols are switched this type is called continuous phase FSK (CPFSK) [6]. The level of noise immunity can be increased if the frequencies representing different information symbols (typically 0 and 1) are not correlated. In this case two subcarrier frequencies are orthogonal [7].

Minimum modulation index $m$ that keeps subcarriers’ orthogonality is equal to 0.5. Figure 1 illustrates spectral density of two orthogonal radio pulses (curves 1 and 2). When $m < 0.5$ these spectra are shifted closer to each other and cause the intersymbol interference and errors after demodulation. CPFSK with $m = 0.5$ is minimum shift keying (MSK), it has more effective spectral characteristic [8].

![Figure 1. Normalized spectra of two orthogonal subcarriers (1, 2) and a 4000 baud MSK signal (3) which is matched with amplitude-frequency response (4) of a piezoceramic antenna. The resonance (central) frequency is 55 kHz, signal bandwidth is 6 kHz.](image)

For a selected piezoceramic antenna with a resonant frequency of 55 kHz and 6 kHz bandpass, the transmission frequencies of “0” and “1” are defined as 54 kHz and 56 kHz respectively. Data transition bitrate is 4000 bauds.

3. A simulation program
In order to design a demodulator, algorithms and operation logic a hydroacoustic communication system, a modeling program is made in a graphical programming language NI LabVIEW (Figure 2). The program allows you to synthesize signals, simulate processes of their propagation in an aqueous medium (with additive white noise, phase drift and superimposed re-reflections), demodulate of the received signal using different methods, estimate bit error rates (BER).
The program works according to a flow chart in Figure 3. In the transmitting part a modulated signal is formed by switching of two sine patterns (Sine Wave.vi functions) according to the input binary sequence. Synchronization of patterns maintains the modulated signal phase to be continuous. The result is displayed in Graph 1 (see example in Figure 4 a).

In the second section multipath propagation effects are simulated. At first, the initial phase of the signal changes randomly, then we add noise. The additive noise of the model hydroacoustic channel is represented with the Gaussian White Noise Waveform.vi pattern. After that the signal is mixed with two copies of itself with random initial phases, amplitude and delay in order to simulate conditions of multipath propagation [9]. The distorted signal is displayed in Graph 2 (Figure 4 b) and sent to a receiver input.

The demodulation part of the program allows one to switch methods of detecting MSK signals. There are three available types of detection schemes:

- filter-type demodulator;
- mathematical discriminator;
- correlation detector.

As result, a continuous series of responses corresponding to “0” and “1” is formed at the output. Their oscillogram is displayed in Graph 3 (Figure 4 c). The decision unit evaluates amplitude of such responses for each binary symbol period and sends the result to the Graph 4 indicator (Figure 4 d panel). Flexibility of adjusting receiving path characteristics and demodulation algorithms allows to accelerate process of developing software and hardware parts of a hydroacoustic communication system and create of a prototype for experimental testing [10].

Figure 4 demonstrates the simulation program front panel and example of detecting with the use of a filter-type quadrature demodulator. Generated package is 1-byte sequence 110001001 with 0.5 ms bit duration. Orthogonal frequencies of 54 kHz and 56 kHz in the MSK signal represent “0” and “1” bits respectively, sampling frequency is 200 kHz. A white noise generator is switched off so the modelling result demonstrates errorless result of detecting and indicates correctness of the simulate program. The same settings have been used for checking all three demodulation algorithms. Conrol terminals (not shown) allow one to change signal and noise amplitudes, sampling frequency, bit duration, carrier...
frequencies.

Figure 4. Front panel of the modelling program. Transmitting of 1-byte sequence 110001001, filter-type detection algorithm. The MSK signal uses 54 kHz and 56 kHz subcarriers: a – modulated signal (the blue color shows “0”, the red fragments are for “1”); b – MSK signal with amplitude and phase distortions; c – oscillations of frequency deviation; d – an indicator of bit correctness.

4. Results and Discussion

After control testing of the detecting algorithms without noise we simulated 1-byte signal propagation with additive white Gaussian noise, phase drift and superimposed re-reflections. In order to accumulate a statistical sample the simulation have been repeated 2500 times (20 thousand bits in total) for different values of signal-to-noise ratio (SNR). The results of simulating are shown in Figure 5. Here, it is clear that the filter-type demodulator lowers noise stability: at SNR 0 dB there are about 10% of error bits and almost 50% at -3 dB. A mathematical discriminator-based demodulator calculates the number of transitions over a given threshold for a pre-filtered input signal. This type of detecting schema demonstrated better results but it still cannot be admitted to be satisfied: about 2% of errors at 0 dB and 3.7% at -3 dB.
The third type of the demodulator calculates the cross-correlation function for each of the possible symbols “0” or “1” and with the use a comparator selects the signal with the greatest match. As it does not require information about the initial phase [11] it has shown much better results. BER = 1.3 × 10^{-4} at 0 dB and 2.5 × 10^{-4} at -3 dB. The correlation detector appeared to be the most effective for applying in our hydroacoustic communication system. However, among analysed demodulators this type requires the greatest processing power. But it is not a significant disadvantage because all calculations will be eventually implemented in a field-programmable gate array (FPGA). Altera Cyclone IV FPGA allows us to freely use real-time processing in such detecting schemes [12].

5. Experimental testing of a prototype
A FPGA-based receiver have been designed in the Altera Quartus 2 environment. The receiver implements digitization of the hydroacoustic signal, gain control, demodulation, and indication of the received signal on the LCD screen. A designed prototype of a hydroacoustic modem for underwater communications consist of transmitter-modulator and receiver-detector parts. The front panel view is shown in Figure 6.

Figure 5. Bit error rates for the use of non-coherent cross-correlation detector (1), filter-type quadrature demodulator (2), mathematical discriminator (3): a – linear scale, b – logarithmic scale.

Figure 6. Experimental testing of prototype of a hydroacoustic modem for underwater communications.

The hydroacoustic modem prototype have been tested experimentally in conditions of a natural reservoir. The aim of a series of tests is to check the modem work stability and evaluate maximum possible distance of consistent reception. Experiments involved two modes of transmitting: amplitude
shift keying single pulses with 500 μs duration and 54 kHz or 56 kHz carrier frequency, and short packets representing an 8-bit sequence with MSK modulation and symbol duration of 500 μs. All electronic devices demonstrated stability, the maximum range of reliable transmitting was 250 m. It is a good result especially if to take into account that no antinoise coding was used.

6. Conclusion
Modelling of operating of a hydroacoustic modem showed that in conditions of transmitting through hydroacoustic communication channel the most effective demodulation method is cross-correlation detecting. Simulation indicated that in this case bit error rate is 5\times10^{-4} at SNR = 6 dB. This result can be improved with error-correcting codes, bit interlacing, diversity reception, etc. The MSK modulation type is more preferable as it provides with narrowband spectral density of signals.

Experimental testing of a prototype proved the operability of the designed power amplifier, the receiver input path, and the implemented signal modulation and demodulation algorithms. During testing in conditions of a natural reservoir we achieved reliable transmitting at 250 meters. At the same time absence of algorithms for automatic tuning and synchronization of the receiver with the transmitter [13] did not allow to get a stable communication channel. So we currently work on designing and integrating a physical layer communication protocol.

7. Acknowledgments
The reported study was financially supported by grant No. 01-FPK-19 for the financial support of research and teaching staff of the INRTU.

References
[1] Stoptsov N A, Boytsov V I, Shelemin V N 1990 Communication under water (Leningrad: Shipbuilding)
[2] Katanovich A A 2012 Marine radio electronics 3 (41) 1623
[3] Borowski B S, Application of channel estimation to underwater acoustic communication. Retrieved from: https://brian-borowski.com/publications/Borowski-Dissertation.pdf (2010).
[4] Bocharov M S, Skipa M I 2009 Possibilities of information transfer under conditions of a priori uncertainty of the parameters of the acoustic communication channel when using adaptive modeling CONSONANCE-2009 ed V Olyinik (Kyiv: Institute of Hydromechanics) chapter 29 pp 109–114
[5] Freitag L, Grund M, Singh S, Partan J, Koski P 2005 Proc. of the OCEANS 2 1086–92
[6] Benson B, Chang G, Manov D, Graham B, and Kastner R 2006 Design of a low-cost acoustic modem for moored oceanographic applications International Workshop on Underwater Networks (NY: Association for Computing Machinery) chapter 1 pp 71–78
[7] Gendron P J 2006 U.S. Navy Journal of Underwater Acoustics 2(56) 267-300
[8] Poletaev A S, Zasenko V E, Chenski A G 2013 Global Scientific Potential 5 (26) 6468
[9] Baran E D 2009 LabVIEW FPGA. Reconfigurable measuring and control systems (Moscow: DMK Press)
[10] Fedosov V P 2010 Digital Sound and Vibration Processing in LabVIEW (Moscow: DMK Press)
[11] Tokmachev D A, Bezrukin A G, Chensky A G Instruments and Experimental Techniques 3 159-60
[12] Steshenko V B 2009 FPGA from ALTERA: designing signal processing devices (Moscow: DODEKA)
[13] Li Y, Benson B, Zhang X, Kastner R 2010 Hardware Implementation of Symbol Synchronization for Underwater FSK International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing (Newport Beach: IEEE) chapter 1 pp 82-88