ONE MORE CONCEPT OF AN EMBEDDED ACOUSTIC CHIRP MODEM FOR UNDERWATER COMMUNICATION

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In this paper we present a concept of an embedded acoustic modem dedicated to underwater communication. The Raspberry Pi is used as a low cost hardware platform. The solution of the physical layer consists in modulation, synchronisation, frames forming, symbol mapping, etc. Specifically, modulation is based upon linear and hyperbolic chirp signal generation. Synchronisation is based upon the correlation of received and transmitted signals. The performance of the communication is tested by computer simulation. This simulation is performed by transmitting signal between two USB sound cards connected by a cable. In the simulation, transmitted signals are intentionally degraded by adding white gaussian noise.

INTRODUCTION

Providing a dedicated wireless communication algorithm is necessary in many modern underwater systems. Acoustic communication is a rapidly developing engineering discipline. This kind of communication is used, for example, in submarine [1], for building underwater sensor networks [2–5], or for controlling remotely operated vehicles [6]. Application of conventional methods of communication based upon radio solutions is impossible in the underwater environment due to the high attenuation of radio waves. Optical wireless communication may be an appropriate solution in many cases but is limited by the water transparency [7]. An acoustic wireless modem may be a suitable solution in specific situations. Underwater communication also allows for the creation of networks. The drawback of such acoustic communication is that the transmission rate is limited due to phenomena such as multipath propagation, Doppler effect, fading, refraction or attenuation. This is the reason why underwater communication is considered as challenging task [8]. In this paper we present a concept of an acoustic modem based upon chirp signal processing. This kind of communication is also called a Sweep-Spread Carrier communication and is especially useful for application in shallow water channels

[9]. The prototype of the proposed acoustic communication system is implemented on an embedded platform equipped with a sound card. The software-defined architecture of the proposed system is flexible, and permitting adjustments and upgrades of modem features [10].

The structure of this article is organized as follows: Section 1 contains the overview of the modulation algorithm, bandwidth management and basic features of the software and hardware employed. The details of the modulator and demodulator software are shown in Section 2 and Section 3 respectively. Results of the simulation and tests of the modem's performance in case that transmission is carried out over the additive white gaussian noise (AWGN) channel is treated in Section 4. Finally, Section 5 describes issues, problems, and future research expectations.

1. MODEM

In this paper we propose a solution based upon the Raspberry Pi (RPi) v. 2, Model B, a single-board computer, and the LogiLink UA0053 USB sound card, which is the common solution for providing audio output and input for the RPi. The operating system used is Raspbian 3.18. This version of RPi is equipped with a 900MHz quad-core ARM Cortex-A7 processor, 1 GB RAM, 4 USB ports, an Ethernet port and 40 GPIO pins. Only the audio output is available without an external audio sound card. Therefore, a third party audio processing device is needed for recording signals. Modems are controlled by a PC host which communicates with them by Ethernet. Two third party libraries were used in order to implement the modem software:

- *ALSA library* – for recording and playing signals through the audio output/input in both the modulator and the demodulator,
- *FFTW* – for correlator implementation based upon the overlap-add algorithm, which is implemented in the demodulator to detect synchronisation and transmitted symbols.

The modem application is implemented in C++ programming language. The modem operates on a 24 kHz bandwidth which is split into two 12 kHz subbands. The modulation depends on four data symbols and one synchronisation symbol which is transmitted at the beginning of the frame. Symbols are converted to chirp signals in the modulator. This kind of signal may be used to design underwater acoustic modem modulation algorithms or their synchroniasation mechanisms [5, 11]. For each of the two modulation channels, an upchirp and downchirp signal are used. There are 101 bytes of data sent in a single transmission frame. The length of the synchronisation symbol is 41.67 ms and a 96 kSa/s sampling rate is used. The transmission rate can be adjusted by specifying the duration of the chirp associated with the information symbol. The structure of the frame is depicted in the Figure 1. In order to use the modem in practice some analogue peripherial hardware is crucial such as amplifiers, frequency step-up and step-down converters, a preamplifier, and a transducer [4].

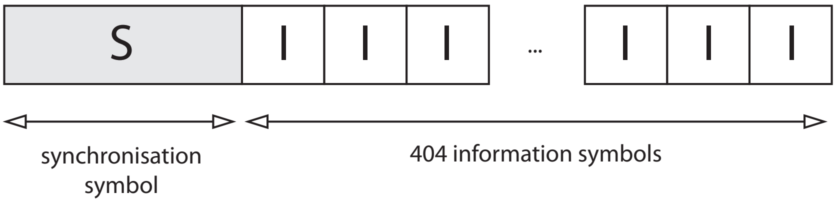

Fig. 1. The structure of the frame.

Fig. 2. The hardware platform used for simulations and tests.

2. MODULATOR

The main element of the modulator is a numerically controlled oscillator (NCO) [12]. The inputs of the NCO are two data substreams formed from the input data stream and the instantaneous frequency value from the instantaneous frequency value generator (IFVG), which is run for each output frame. A pair of bits obtained from the data substreams is associated with a single chirp generated by the NCO. The generated chirp can be an up- or down- chirp transmitted in the high or low frequency channel. The IFVG determines a kind of the generated chirp frequency modulation. This solution permits switching between various types of the chirp frequency modulation. A generated chirp can be a linear frequency modulation chirp (LFMC) or a hyperbolic frequency modulation chirp (HFMC). Examples of transmission based upon LFMC and HFMC are shown in Figures 3. and 4, respectively. A synchronisation symbol is sent at the beginning of each frame and is also represented by a chirp. The synchronisation signal has double the bandwidth of the data signal. The length of the symbol influences the system resistance to synchronisation loss. The level of E_b/N_0, causing 50% of incorrect frame beginning time detections in the modem, was measured. Results for various synchronisation symbol lengths are presented in the Table 1.

Tab. 1. Lengths of the synchronisation symbol and corresponding levels of E_b/N_0 which cause 50% of incorrect frame beginning time detections

the length of the synchronization symbol [ms]	$\mathbf{E_b/N_0}$ **[dB]**
62.5	10
31.3	11
15.6	12.43
7.8	16.15

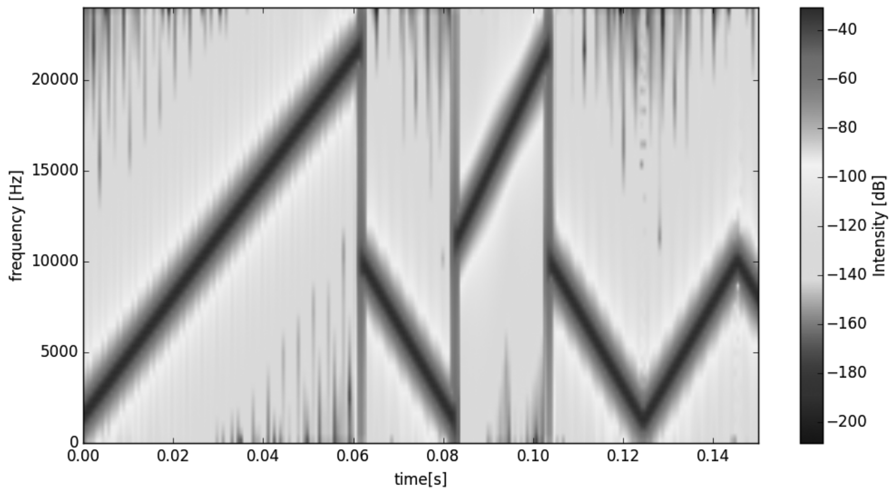

Fig. 3. LFMC signals generated by the modem.

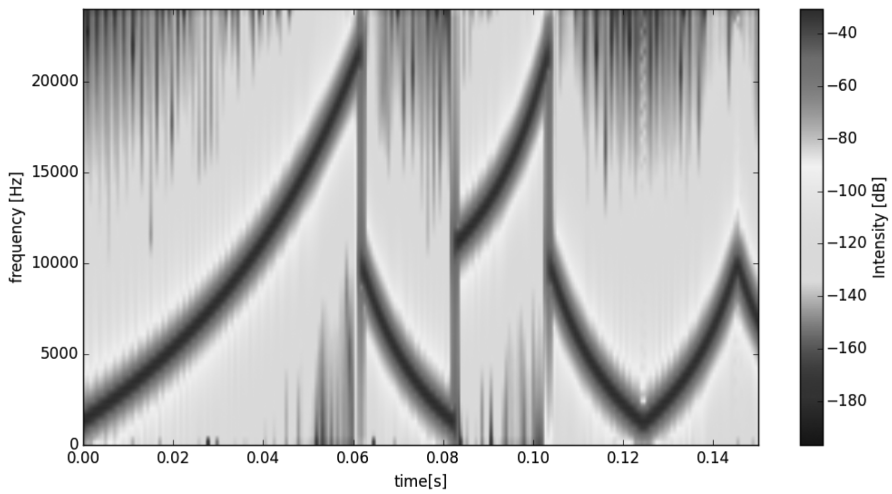

Fig. 4. HFMC signals generated by the modem.

A complex oscillator is used to implement the NCO. The complex oscillator algorithm is based upon the rotating phasor concept [13]. The frequency of an output signal can be controlled by changing the incrementation step. These changes are made by the IFVG module in order to obtain LFMC or HFMC signals. The incrementing of the oscillator phase is obtained by multiplying the oscillator state by a step factor. The state of the oscillator is not reset between consecutive symbols.

The complex oscillator has the advantage that the amplitude of the output signal is unitary. Therefore, the amplitude of the NCO output signal can be controlled by a multiplication of the complex oscillator output signal by a desired value.

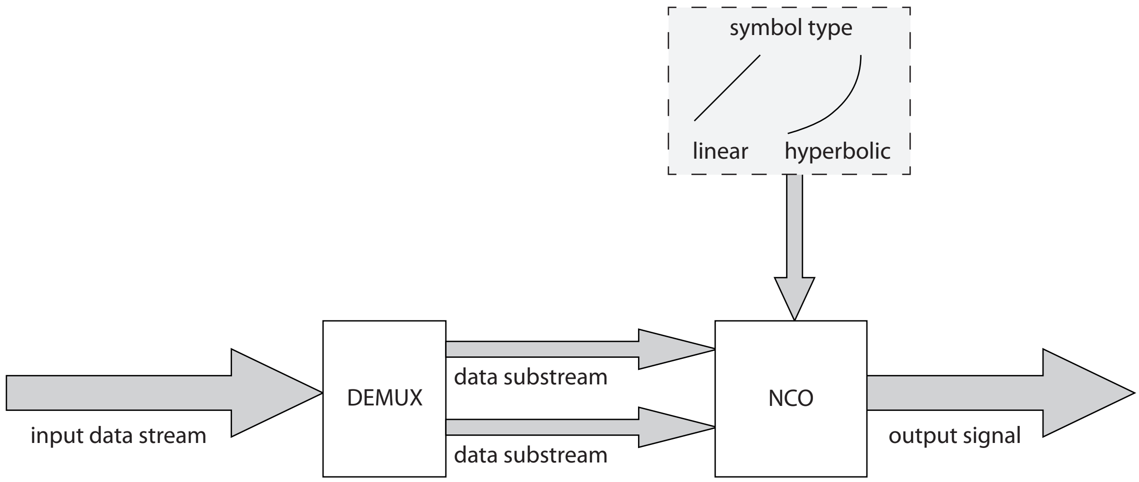

Fig. 5. A block diagram of the modulator algorithm.

3. DEMODULATOR

Decisions taken in the demodulator are based upon the demodulation metric. The metric is used both for synchronisation symbol detection and for information symbol detection. The equation used to compute the metric is given by the following formula:

$$M(s[n]) = \frac{\max\{s[n]\}}{E\{s[n]\}} \cdot \frac{1}{N} \sum_{i=0}^{N} (s[n])^2. \tag{1}$$

If the maximum value of the signal is high and the arithmetic mean is low, then the first factor of Equation 1 also has a large value and therefore can be used to detect impulse-like signals in the output of the matched filter in the demodulator. Second factor: $\sum_{i=1}^{N}(s[n])^2/N$, is equal to the received signal power. If the shape of the signal is impulse-like and the power is high, the value of the metric is also high. Synchronisation symbols can be detected by computing the metric for consecutive parts of received signal. Detection of the rest of symbols is implemented in a similar manner. The demodulation process is divided into two parts:

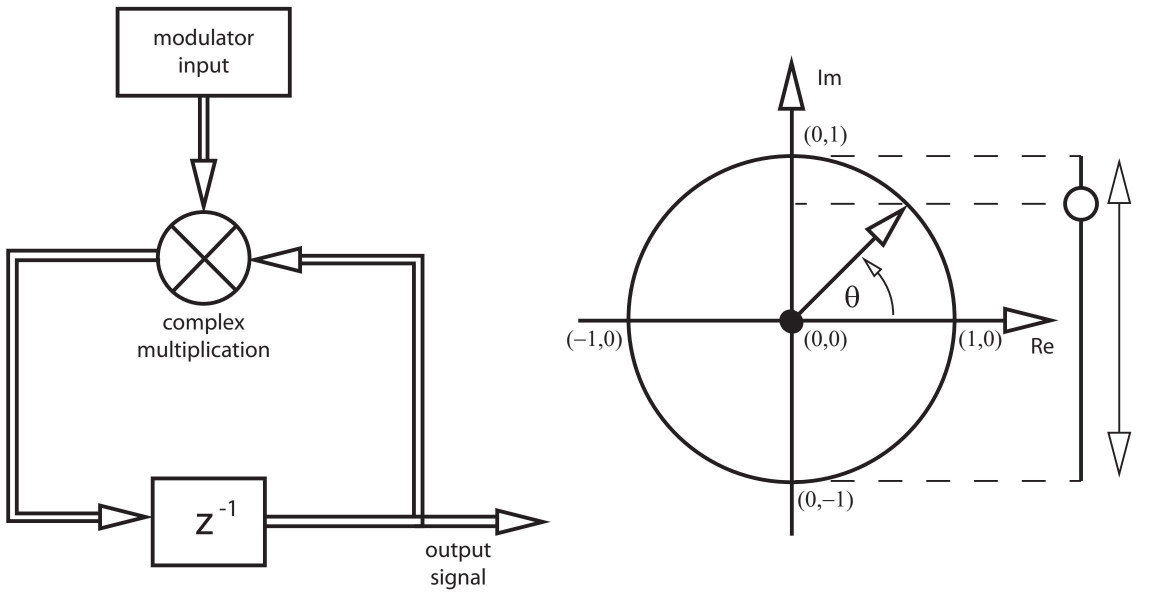

Fig. 6. The complex oscillator DSP algorithm.

- *step 1* – the preamble seek procedure. This step is based upon the signal obtained from the correlator. If the output signal has sufficently high power and has a proper impulse-like shape, it is concluded that a data frame was received. The decision is based upon the detection metric calculated from the output of the matched filter. The arrival time of the received frame is computed after detection of the synchronisation symbol.

- *step 2* – detection of symbols in the received frame depending on the preamble position computed in the previous step. Information symbols are extracted from the transmitted frame. Next, a detection metric is calculated for each symbol and a pair of bits associated with the highest value is chosen.

If an LFMC or an HFMC associated with the synchronisation symbol is present in the received signal, the matched filter generates a spike-shaped cross-correlation function in the output. The signal from the matched filter is split into frames and a signal detection metric is computed for each frame. If the value of the metric is sufficently high, the algorithm performs further operations in order to determine the time of reception of the synchronisation symbol. These operations are:

- *envelope detection* – used to estimate the received signal power,
- *normalization of outputs of envelope detectors* – permitting the use of the normalized threshold in the next step of the processing,
- *thresholding* – each sample below the normalized threshold of 0.5 generates 0 on the output, each sample greater than the threshold generates 1,
- *preamble position estimation* – calculated by the detection of the first rising edge of the pulse-shaped result of the thresholding operation.

The same metric is used in the symbol detection process. The block diagram of this process is depicted in Figure 7. The synchronisation symbol position is known after the first step and the rest of the frame can be split into a set of information symbols. Each information symbol is processed by four matched filters at the same time. Matched filters are associated with symbols of the modulation. The metric is computed for the output of each filter. Then a pair of bits assigned to the matched filter with a greatest metric value is chosen. A mapping relationship between pairs of bits and parameters of a chirp are shown in the Table 2. This process is repeated for each symbol signal in the processed frame.

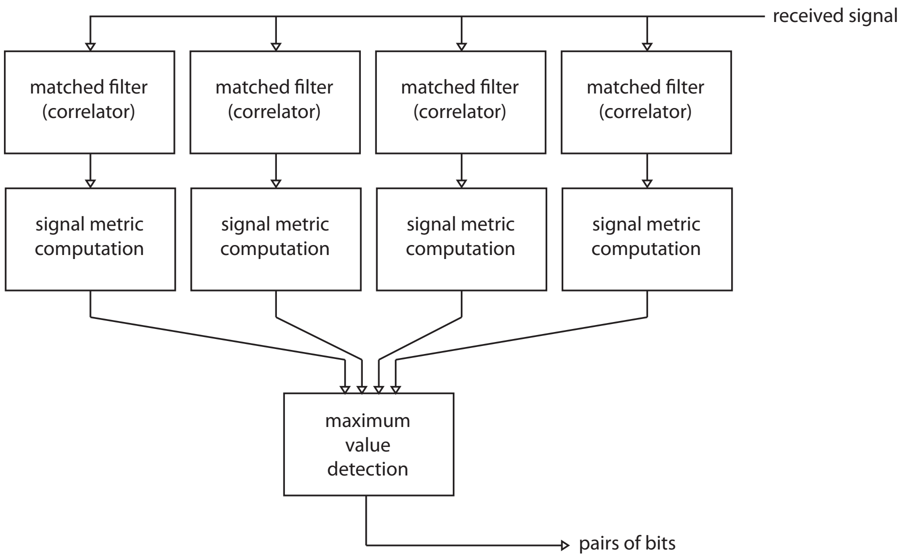

Fig. 7. A block diagram of the symbol detection process signal flow.

Tab. 2. Symbol mapping relation. Chirp rate depends on the current transmission rate. The start and the end frequency of the chirp connected with a pair of bits is fixed.

a pair of bits	start frequency [kHz]	end frequency [kHz]
00	10	1
01	1	10
11	11	22
10	22	11

4. PERFORMANCE OF THE DESIGNED SYSTEM

The system performs off-line processing of transmitted signals. The simulation of the transmission over the AWGN channel is carried out in order to evaluate the performance of the modem. The computation is made for three transmission rates and for both implemented types of chirp frequency modulation. The results of the simulation are depicted in Figure 8. For all tested transmission rates the LFMC performed better than the HFMC. The bit error rate (BER) obtained for the LFMC was smaller than for HFMC. This arises from the fact that the autocorrelation function of an LFMC has a smoother shape. Therefore, an LFMC provides better reception conditions in the receiver if no Doppler effects are present in the transmission channel. On the other hand, an HFMC is more resistant to the Doppler effect [14, 15]. Therefore, it is important to take this tradeoff into consideration in designing acoustic communication systems based upon chirp signal processing.

The second measurement scenario is the test of the influence of a sound card on system performance. The audio output and the audio input were connected by the wire. Modem transmitted signals through this connection and a BER were estimated. Results of measurements pertaining to the simulation are shown in the Figure 9. The transmission rate is equal to 96 b/s. In order to obtain desired values of E_b/N_0, the signal is degraded by the AWGN. The main influence on the performance of the modem is the frequency response of the sound card converters. Audio devices introduce the dumping of high frequencies. The frequency response of the sound card was measured using the AWGN and is depicted in the Figure 10. The lower subband of modulation is almost unaffected but the dumping of the highest frequencies of the upper subband (close to 20 kHz) is about 6 dB. This can cause problems with reception of signals transmitted in the high frequency subband.

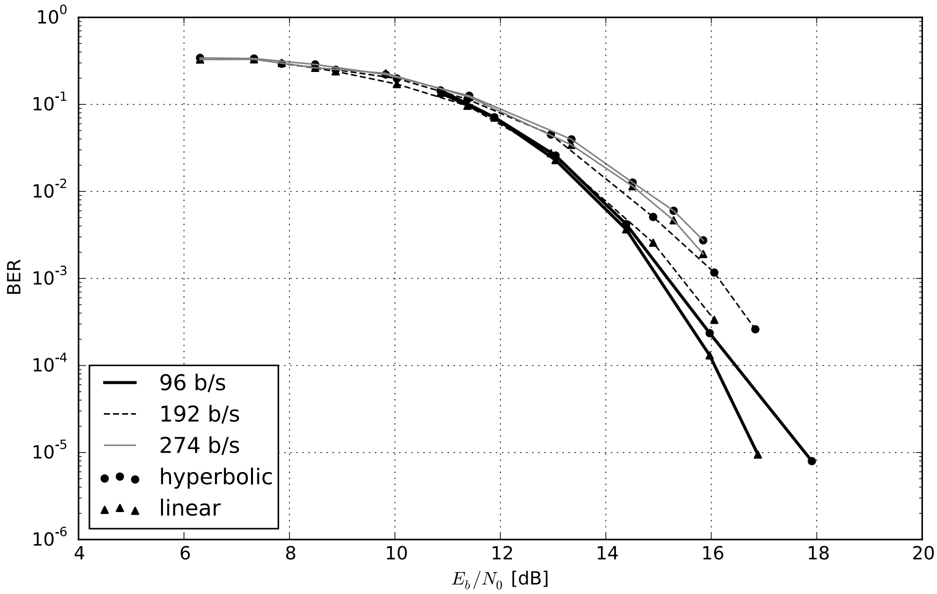

Fig. 8. Results of simulation performed for various transmission rates and chirp types.

5. CONCLUSIONS

Development of a modem software for cost-efficient embedded platforms is possible and single-board computers are a technical solution for algorithm development and testing. Even with the current state of software development it is nevertheless important to consider the properties of converters. It is necessary to provide custom or high-end hardware solutions in order to obtain high quality generated signals and to improve reception conditions. Therefore, the audio sound card is not a good choice if development of the acoustic communication system is considered. Third party analogue hardware is a crucial element of a digital communication system and is equally determinative of the quality of the designed technical solution as a modulation algorithm [4].

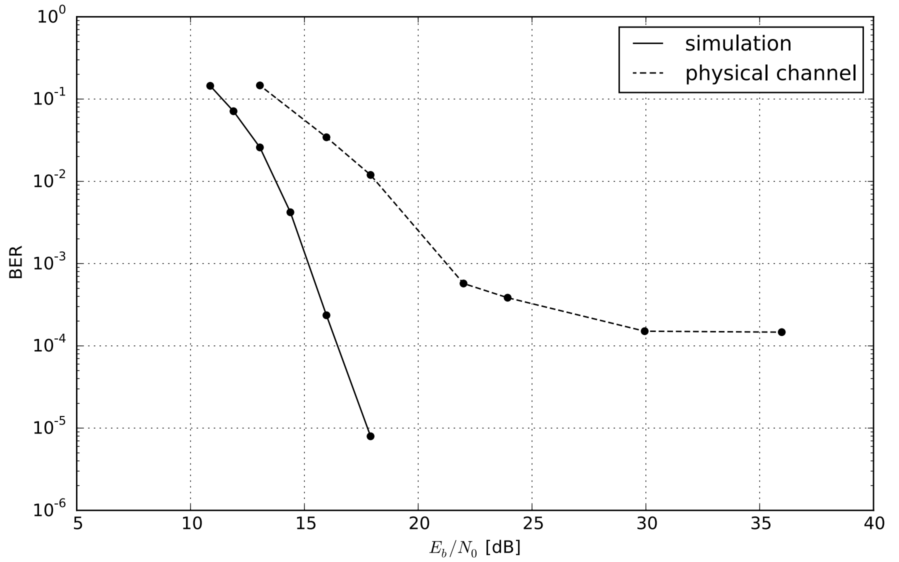

Fig. 9. Results of simulated transmission over AWGN channel compared to the wired channel simulation, which takes into account the frequency response of the sound card.

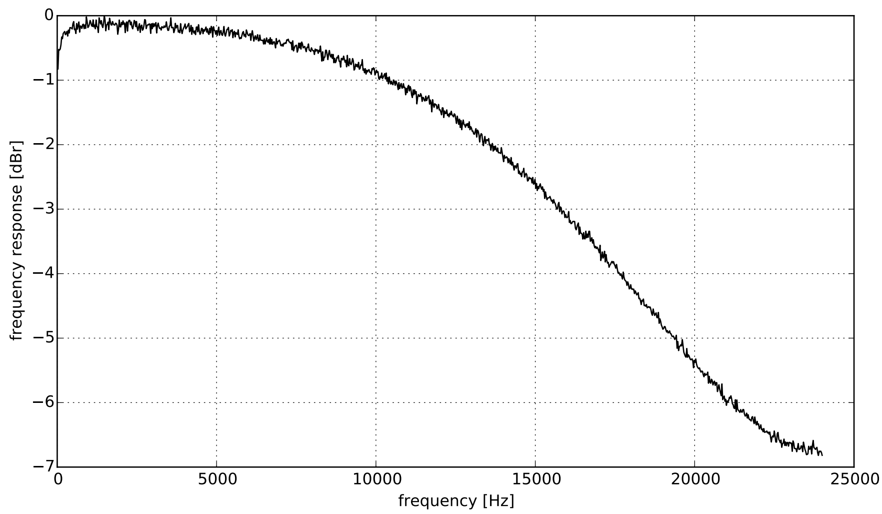

Fig. 10. The frequency response of the USB sound card.

The processing presented in this work is performed off-line. The next step is to modify modem algorithms to run online, preferably incorporated in the real-time operating system. Tests with other hardware platforms like Banana Pi and Beaglebone are also planned. We would like to evaluate possibility of compensating for the frequency response of the sound card.

Decisions in the symbol detection step in the demodulator algorithm are based upon the correlation function computed by matched filters. This correlation function contains a short spike and the long part of a noise-like signal. We would like to test if it is possible to improve system performance using only the part of the signal close to the spike for the metric computation.

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REFERENCES

[1] A. Raganowicz, L. Kilian, J. Marszal, A. Schmidt, T. Sidorko, M. Rudnicki, "Workstation For Training ASW Helicopters Navigators and Analysing Real Flight Data", Hydroacoustics, Vol. 12, 181-188, 2009.

[2] M. Goetz, I. Nissen, "GUWMANET — Multicast routing in Underwater Acoustic Networks", Communications and Information Systems Conference (MCC), Vol. 1, 8-9, 2012.

[3] I. Kochańska, H. Lasota, R. Salamon, "OFDM modulation and adaptive equalization for underwater communications", Hydroacoustics, Vol. 8, 77–82, 2005.

[4] A. Sanchez, S. Blanc, P. Yuste, J. Serrano, "A low cost and high efficient acoustic modem for underwater sensor networks", OCEANS, Vol. 1, 6-9, 2001.

[5] L. Wu, J. Trezzo, D. Mirza, P. Roberts, J. Jaffe, Y. Wang, R. Kastner, "Designing an Adaptive Acoustic Modem for Underwater Sensor Networks", IEEE Embedded Systems Letters , Vol. 4, 1-4, 2012

[6] Z. Wei-Qing, W. Chang-hong, P. Feng, Z. Min, W. Rui, Z. Xiang-Jun, D. Yong-Mei, "Underwater acoustic communication system of AUV", OCEANS '98 Conference Proceedings , Vol. 1, 477-481,1998.

[7] F. Akhoundi, J. Salehi, A. Tashakori, "Cellular Underwater Wireless Optical CDMA Network: Performance Analysis and Implementation Concepts", IEEE Transactions on Communications, Vol. 63, 882-891, 2015.

[8] M. Chitre, S. Shahabudeen, M. Stojanovic, "Underwater Acoustic Communications and Networking: Recent Advances and Future Challenges", Marine Technology Society Journal, Vol. 42, 103-116 ,2008.

[9] K. Kebkal, R. Bannasch, A. Kebkal, "Estimation of phase error limits for PSK-modulated sweep-spread carrier signal", OCEANS, Vol. 2, 748-756 Vol.2, 2004

[10] H. Dol, P. Casari, T. van der Zwan, "Software-defined open-architecture modems: Historical review and the NILUS approach", Underwater Communications and Networking (UComms), Vol. 1, 3-5, 2014

[11] W. Lei, D. Wang, Y. Xie, B. Chen, X. Hu, H. Chen, "Implementation of a high reliable chirp underwater acoustic modem", OCEANS, Vol. 1, 21-24, 2012.

[12] S. Kadam, D. Sasidaran, A. Awawdeh, L. Johnson, M. Soderstrand, "Comparison of various numerically controlled oscillators", The 2002 45th Midwest Symposium on Circuits and Systems, Vol. 3, 200-202, 2002.

[13] R. Lyons, A. Bell, "The swiss army knife of digital networks", Signal Processing Magazine, IEEE , Vol. 21, 90-100, 2004.

[14] J. Yang, T. K. Sarkar, "Acceleration-invariance of hyperbolic frequency modulated pulse compression", Digital Signal Processing, Vol. 18, 291-309, 2008.

[15] A.Nagajyothi, K. Raja Rajeswari, "Delay-Doppler performance of hyperbolic frequency modulation waveforms", IJEEDC, Vol. 1, 62-66, 2013.