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A Digital Acoustic Transceiver for Underwater Acoustic Communication

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Abstract

In this paper, we present a phase coherent all-digital transceiver for underwater acoustic communication, which allows the system to reduce complexity and increase robustness in time variant underwater environments. It is designed in the digital domain except for transducers and amplifiers and implemented by using a multiple digital signal processors (DSPs) system. For phase coherent reception, conventional systems employed phase-locked loop (PLL) and delay-locked loop (DLL) for synchronization, but this paper suggests a frame synchronization scheme based on the quadrature receiver structure without using phase information. We show experimental results in the underwater anechoic basin at MOERI. The results show that the adaptive equalizer compensates frame synchronization error and the correction capability is dependent on the length of equalizer.

Keywords: *Underwater acoustic communication, Adaptive equalizer, Frame synchronization*

I. Introduction

The underwater acoustic channel can be characterized as a time-varying multi-path channel with fast fading and Doppler Effect[1]. Especially, horizontal channels have multiple scattering by surface and bottom, which causes multi-path delay spread up to several tens of symbol intervals, while vertical channels have little time dispersion. For these reasons, frequency shift keying/differential phase shift keying (FSK/DPSK) modulation was commonly considered as robust techniques of digital underwater transmission, as an energy detection rather than phase coherent reception[2].

In recent years, many kinds of phase coherent receiver were introduced. [3] is the first work to demonstrate feasibility of phase coherent techniques. It optimized jointly carrier synchronization and fractionally spaced decision feedback equalizer (DFE) which parameters are adaptively adjusted using a combination of the recursive least squares (RLS) algorithm and second-order digital PLL, and applied to experimental data from several underwater acoustic channels. The acoustic transmitters and receivers can be implemented without the analog mixer in digital domain except for transducers and amplifiers because the carrier frequency of underwater acoustic telemetry is typically lower than 10MHz and there are many high-speed commercial analog to digital converters (ADCs) and digital signal processors (DSPs). In the underwater acoustic communications, system parameters should be changed according to the channel conditions. Almost all system parameters such as the modulation technique, sampling rate, and carrier frequency, etc., can be easily changed by simple program modifications in the case of all-digital implementation.

These facts induced all-digital implementation of acoustic telemetry. A digital acoustic image transmission system between autonomous underwater vehicle (AUV) and mother ship was proposed[4]. The modulation techniques were phase shift keying (PSK) and quadrature amplitude modulation (QAM). Its disadvantages are the complicated synchronization processes, the expensive optical repeater, and limitation to vertical channels. It

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is under test and should be verified in the real underwater channels. DPSK modulation method was used in[5].

In this paper, we present a phase-coherent digital transmitter and receiver for underwater acoustic communication. Also we describe a frame synchronization method based on the 13-symbol barker code without using any phase information. We show experimental results to verify performances in the underwater anechoic basin at MOERI (former KRISO)/KORDI.

II. All-Digital Transceiver

A. Transmitter

The block diagram of the all-digital transmitter is shown in Figure 1. The signal frame consists of 13-symbol Barker codes, training sequence and data, which are time multiplexed as shown in Figure 2. Frame synchronization is accomplished by matched filtering to Barker code. Transmission gaps exist between Barker code and training sequence and between Data and Barker code for successful matched filtering in the frame synchronization processes. Training sequences are used for an adaptive equalizer and beam-former. The signal frame is organized in blocks so as to provide periodic frame synchronization and retraining for the adaptive signal processing techniques, which allows coping effectively with time varying underwater channel.

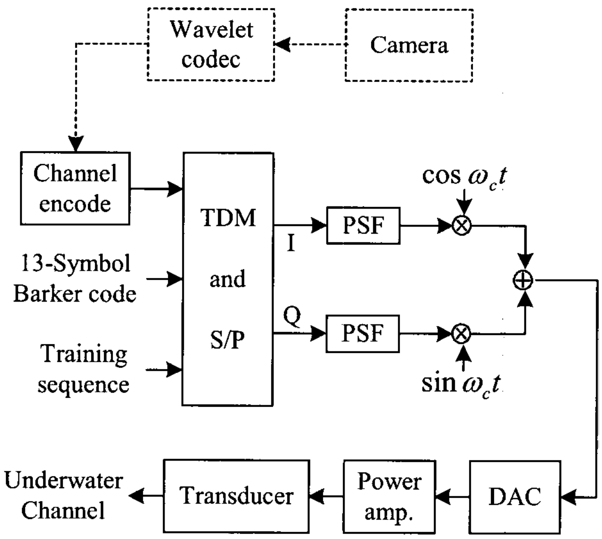


Figure 1. Block diagram of the all-digital transmitter.

Barker code	Tx. gap	Training sequence	Data	Tx. gap

Figure 2. Signal frame.

The digital modulation technique is quadrature phase shift keying (QPSK). The channel encoded data, Barker code, and training sequences are time multiplexed through the time division multiplexing (TDM) module and mapped to I and Q branches by the serial-to-parallel (S/P) block. I and Q branches are then filtered by the pulse shaping filter (PSF) and QPSK modulated. The PSF is a raised cosine filter and truncated to satisfy following requirement on modulation accuracy

$$\sqrt{\frac{\int_{-\infty}^{\infty}\left\{h(t)-\tilde{h}(t)\right\}^2 dt}{\int_{-\infty}^{\infty} h^2(t)dt}} < \alpha, \qquad (1)$$

where the threshold value can be changed according to the given conditions.

The maximum carrier frequency is bounded by the conversion time for a "full scale" signal jump of the digital to analog converter (DAC). It is also restricted by the conversion time of the ADC in the receiver. The wavelet codec and camera indicated by dashed box are need for image application.

B. Receiver

The block diagram of the all-digital receiver is shown in Figure 3. The received signal, after being passed through the underwater acoustic channel, is filtered and sampled in the A/D converter. The low-pass filter (LPF) cuts off the high frequency components of the received signals. The sampling rate of the ADC can be determined as follows. 1) It should be larger than

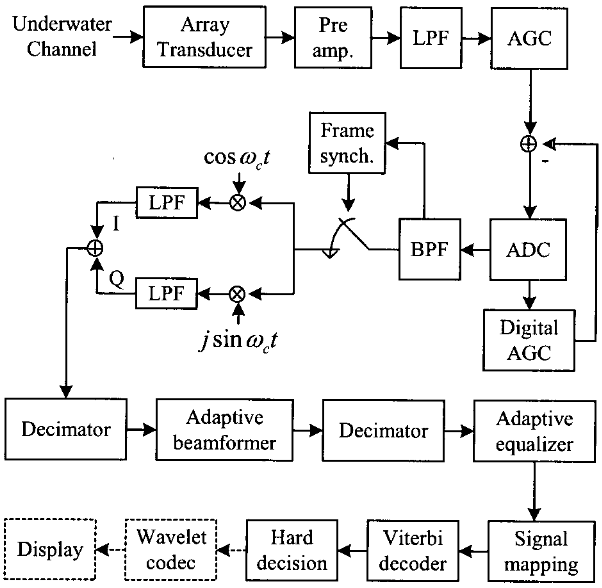


Figure 3. Block diagram of the all-digital receiver.

the Nyquist rate from the Nyquist theorem. 2) It should be a multiple of for easy implementation of the decimator, where the data rate and over-sampling rate are the number of sample for one symbol period.

The quantization noise and saturation noise caused by ADC can be compensated by the digital automatic gain control (AGC) module. Following the ADC there is the band pass filter (BPF) which extracts the only interested frequency band within bandwidth.

The course frame synchronization process is performed as shown in Figure 4. "Received signal" in Figure 4 is the digital signal sampled and filtered by BPF. The channel probe for the frame synchronization is a 13-symbol Barker code (See the signal frame of Figure 2.), where "13-symbol Barker code" means that the same 13-bit Barker code is inserted into the both I and Q channels data at transmitter. The autocorrelation of Barker code has the property that the largest sidelobe has a magnitude of unity. It makes possible to obtain the course frame synchronization without using any phase information. It is come down to a simple energy detection problem. Prior to the matched filtering process, I-channel output and Q-channel output are squared and added to ignore the carrier phase error.

The adaptive beam-former is the class of wide-band beam-former which has tapped delay lines behind each sensor [6], [7]. The adaptive wide-band beam-former parameters, e.g., inter-tap delay and the number of taps per element, for the given fractional bandwidth can be determined from the previous results [8-10]. Note that the inter-tap delay can be easily modified by the programmable sampling rate. The weight update is accomplished through the RLS algorithm.

The adaptive equalizer has a T/4-spaced transversal filter structure and the weight update algorithm is also RLS, where T is the symbol duration. The exact symbol timing recovery could be eliminated by the use of a fractionally spaced equalizer[11]. If the signal frame duration is sufficiently small, and then we can assume that there is negligible phase fluctuation and the use of PLL and DLL could be eliminated.

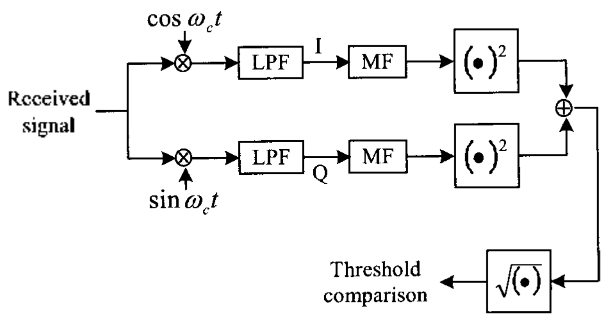


Figure 4. Frame synchronization.

The Viterbi decoder is used as the maximum likelihood decoding algorithm for the convolutional code. It operates on the 8-level soft decisions, which results in a performance improvement of approximately 2 dB in required signal to noise ratio (SNR) compared to hard decisions and a loss of approximately 0.2 dB compared to infinitely fine quantization. The decoding delay is 5K, where K is the constraint length of the convolutional encoder[11].

III. Experimental Results

A. Experimental Set-up

A simple transmitting and receiving experiment was performed in the anechoic tank at MOERI/KORDI. The anechoic tank has a rectangular shape and its size is 914cm long, 282cm wide and 500cm deep. It has cone-type anechoic lining at the four walls and bottom. It was designed to absorb acoustic waves frequency of which is higher than about 3 kHz[12].

During the experiment two omni-directional acoustic transducers (one transmitter and one receiver) were used so that there were two communication paths: direct and surface-reflected ones. The transducers were located at 83.6cm deep and the distance between them was 75.6cm (See Figure 5). One frame data (37,200 points) was generated by the QPSK modulation method with the center frequency of 37 kHz. The generation frequency at the AD converter was 149.25 kHz (period: 6.7s) and

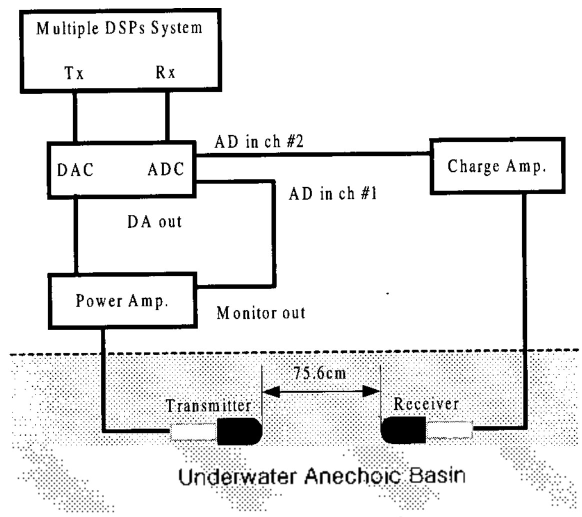


Figure 5. Equipment set-up for transmitting and receiving acoustic signals in the anechoic tank using two omni-directional transducers.

a power amplifier was used for amplifying transmitting signals. The received data was also amplified and filtered (100 kHz LPF) via a charge amplifier and sampled at the same frequency with generation one, or 149.25 kHz.

The important experimental parameters are summarized as follows. The data rate is 9,600 bps (4.8 kHz bandwidth) and the duration of one frame is 250ms (1,200 symbols or 2,400 bits). The training sequence is 50-bit pseudo-noise (PN) sequences.

B. Experimental Results

Figure 6 shows signal constellations of the equalizer input and output, where the input has unknown carrier phase mismatch and the equalizer has 15 taps. Although SNR of unsynchronized input signal is severely low (commonly 30 dB lower than the synchronized one) we can obtain the same result with perfect carrier phase synchronization, i.e., SNR of the equalizer output is always same regardless of carrier phase. It comes from the fact that the frame synchronization process is not dependent on carrier phase error.

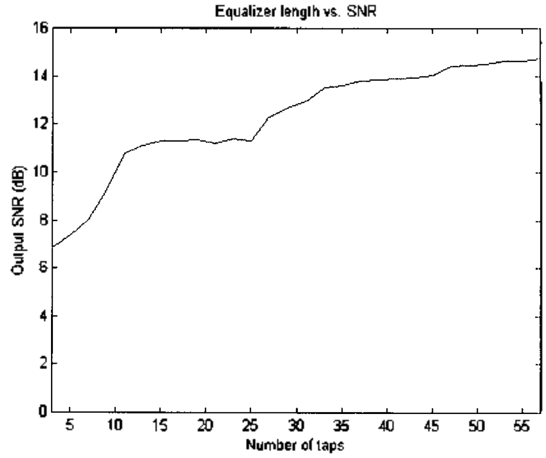
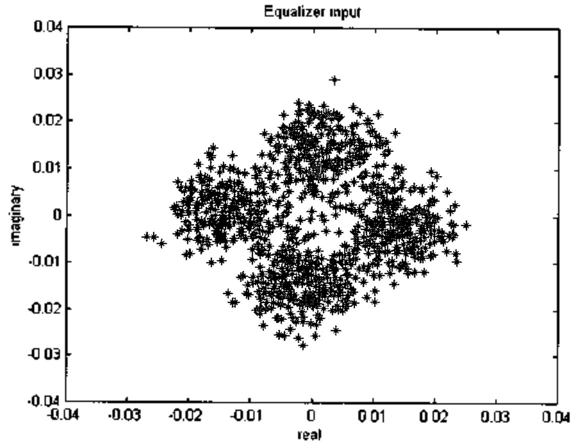
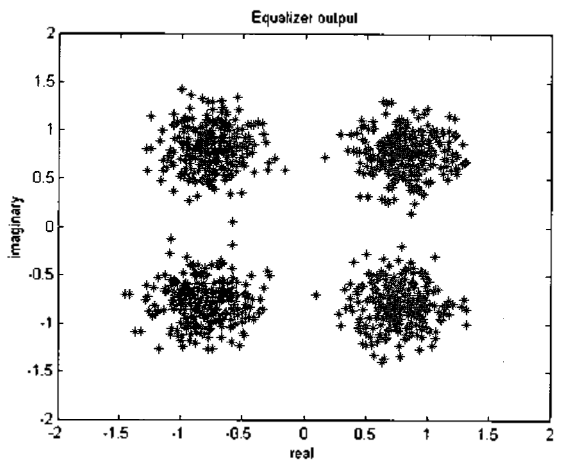


Figure 7. Equalizer output SNR versus equalizer length.

Figure 7 shows the equalizer output SNR according to the number of tap. If the taps exceed 14 (3.5 symbols), the output SNR is slightly increased. It can be explained as follows. Because of the sound absorption at four walls and bottom, there

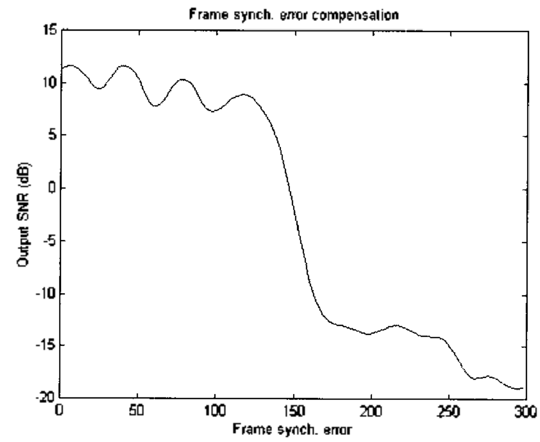


(a) Input

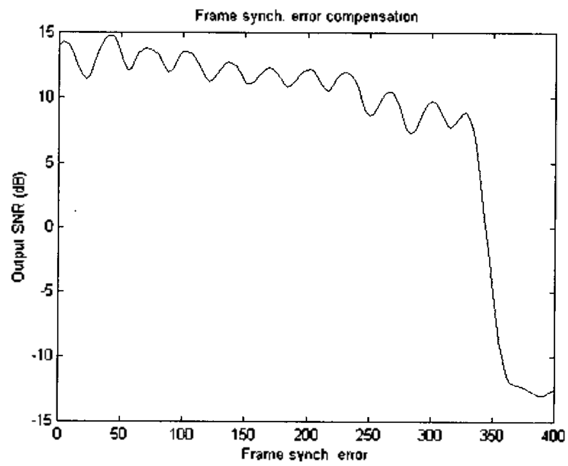


(b) Output

Figure 6. Signal constellations.



(a) 15 taps



(b) 40 taps

Figure 8. Frame synchronization error compensation of the equalizer.

are only two multi-paths in the communication channel. One is the path that goes from the transmitter to the receiver directly and the other is the one that is reflected at the free surface once. In this experiment, the delay of the surface reflection is 0.73ms and it corresponds to about 3.5 symbols duration .

To investigate the effect of frame synchronization error compensation of the equalizer, we observe the equalizer output SNR as shown in Figure 8. In the figure, (a) and (b) are the cases of 15 taps and 40 taps, respectively. The value of 31 is equal to one symbol in the horizontal axis. When the frame synchronization error is lower than the time equivalent to the equalizer length the decreasing rate of SNR is slow. But, if it becomes larger than the threshold value, SNR decreases very fast. In the case of (a), SNR varies within 1 dB when it is smaller than two symbols and it can be compensated up to 7 symbols without 3 dB loss of SNR in the case of (b). Hence, there is trade-off between frame synchronization error compensation and equalizer length. The equalizer has more taps, it corrects frame synchronization error more stably and widely.

IV. Conclusions

We have designed a phase-coherent all-digital transceiver for underwater communication in the digital domain except for amplifiers and it was implemented by using the multiple DSPs system. The proposed frame synchronization algorithm had no need of PLL or DLL.

We have performed experiments using the designed systems in the underwater anechoic basin at KRISO. We have proved that the frame synchronization is well done without PLL. Also, it was found that the adaptive equalizer could compensate frame synchronization error and the correction capability was dependent on the length of equalizer and over-sampling rate.

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