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Experimental Study of Long-range Shallow Water Acoustic Communication Based on OFDM-Modem

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Abstract. In this paper, we focus on the need for remote and robust underwater acoustic(UWA) communication in shallow sea. A set of OFDM underwater acoustic communication algorithm is designed including the techniques of Doppler estimation and compensation, channel equalization and frequency diversity. This algorithm is realized in the DSP and successfully applied on the OFDM-Modem platform. In Da- Lian shallow sea trial, the horizontal communication distance is 36 kilometers under the condition of QPSK modulation, 1/2 rate convolution code, bandwidth between 4 and 8kHz. The communication rate of the OFDM-Modem can reach 426bps and the ultimate BER is less than 10-3.

Introduction

Underwater acoustic sensor networks has become a new field to research with great foreground with the development of ocean exploitation, environmental data collection, pollution monitoring, military surveillance. The design and implementation of a robust underwater acoustic network node is the foundation to realize that.

Achieving reliable communication over underwater acoustic channels has long been recognized as a challenging problem owing to the scare bandwidth available and the double spreading phenomenon in time and frequency domains. The characteristics of the shallow sea, including the great multipath time delay, the repaid immediate deformation, the serious frequency selective fading(due to multipath channel) ,the high background noise(due to wind, waves and ship traffic) and high doppler shift(due to ocean currents and vehicle movement) make long range shallow water acoustic communication more difficulty to research[1].

Many companies abroad are studying underwater acoustic communication Modems. UWN series product which is based on the technique of Broadband Acoustic Spread Spectrum from LinkQuest[2]. The underwater acoustic wireless MODEM AquaComm and the AquaNetwork which can work together via the net are the products from DSPCOMM [3]. The Micro-Modem is a compact, low-power, underwater acoustic communications and navigation subsystem. It has the capability to perform low-rate frequency-hopping frequency-shift keying, variable rate phase-coherent keying, two different types of long base line navigation, narrow-band and broad band [4]. Reconfigurable underwater acoustic modem from MIT provides a flexible environment for the testing of different communication algorithms including networking protocols[5-6].The OFDM underwater acoustic algorithm is implemented on the TMS320C6713 DSK[7]. The implementation results of OFDM acoustic modems under both single-input single-output and multi-input multi-output (two transmitters and two receivers) settings is given in [8]

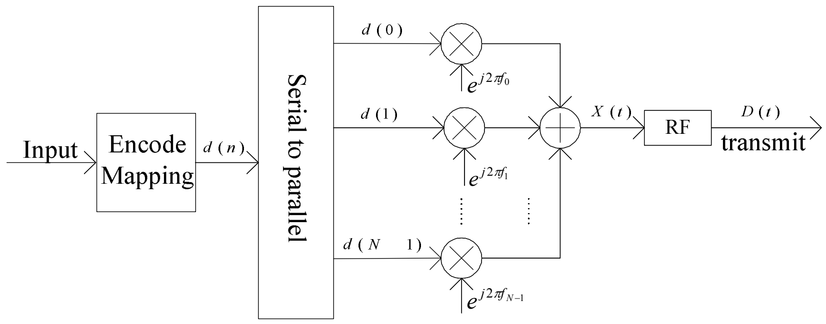
This paper presents design, implementation and sea trial of a OFDM modem. This OFDM acoustic modem features QPSK modulation, convolution coding, and frequency diversity. In the following section, we present the OFDM-modem hardware. The sea trial and data results are given in sections IV. The paper is concluded in Section V.

The Principle of OFDM

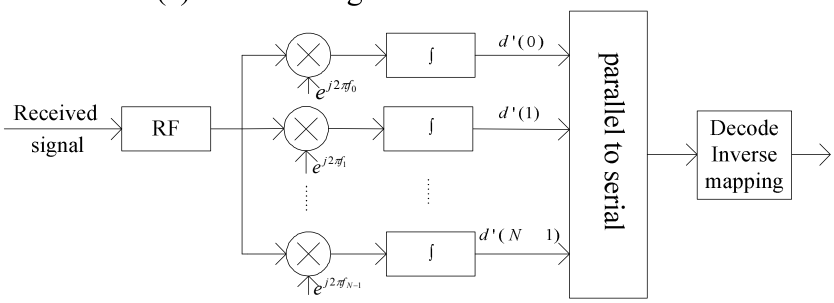
Orthogonal frequency-division multiplexing (OFDM) is a method of encoding digital data on multiple carrier frequencies. The data is divided into several parallel data streams or channels, one for each sub-carrier. Each sub-carrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation or phase-shift keying) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

The primary advantage of OFDM over single-carrier schemes is its ability to cope with narrowband interference and frequency-selective fading due to multipath which is exactly the main characteristic of underwater acoustic channel. Channel equalization is simplified because OFDM may be viewed as using many slowly modulated narrowband signals rather than one rapidly modulated wideband signal. The low symbol rate makes the use of a guard interval between symbols affordable, making it possible to eliminate intersymbol interference (ISI) and utilize echoes and time-spreading to achieve a diversity gain. This mechanism also facilitates the design of single frequency networks, where several adjacent transmitters send the same signal simultaneously at the same frequency, as the signals from multiple distant transmitters may be combined constructively, rather than interfering as would typically occur in a traditional single-carrier system.

The orthogonality requires that the sub-carrier spacing is Δf =fs/N_FFT Hz, where fs is the sample ratio, N_FFT is the point of FFT. Therefore, with N sub-carriers, the total signal bandwidth will be B=N·Δf Hz. The orthogonality allows for efficient modulator and demodulator implementation using the FFT algorithm on the receiver side, and inverse FFT on the sender side. Fig. 1 explains the transmission and reception principle.



(a) Block diagram of OFDM transmitter



(b) Block diagram of OFDM receiver

Fig. 1 Block diagram of OFDM transmitter and receiver

The original sequence of complex numbers could be restored by sampling the received signal in a certain period and transforming the digital signal with the DFT. Then the carrier inverse mapping could convert the sequence back to the original signal. From all above, we can get that the modulation and demodulation could be realized by the IFFT/FFT, which can reduce the running time with the fast flourier transform algorithm[9].

Fig.2 shows the procedure of transmitter and receiver processing including data encoding and decoding, interleaving and deinterleaving, QPSK mapping and unmapping, frequency diversity and combination, doppler estimation and compensation and channel estimation and equalization.

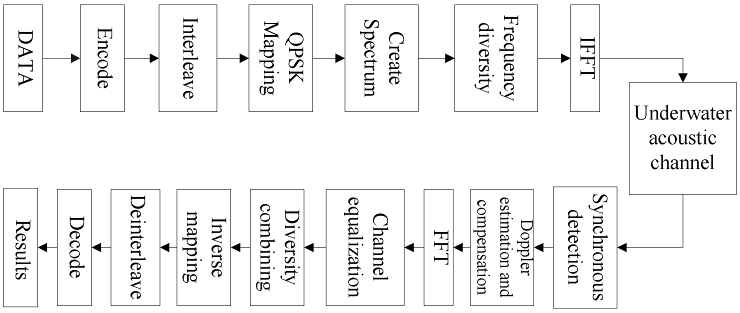


Fig. 2 Block diagram of OFDM UWA communication system

Hardware Platform For Sea Trial

In order to prove the effectiveness of the OFDM algorithm under the shallow sea environment, this paper present the implementation of the algorithm based on the underwater OFDM-Modem platform from Science and Technology on Underwater Acoustic Laboratory, Harbin Engineering University. Consisting with 48V cells, communication signal processing unit, power amplifier board, analog processing board, transmitting transducer, receiving hydrophone and shell mechanical structure. The connection of modules is described in Fig.3. Fig.4(a) shows the actual picture of the acoustic OFDM-Modem, and (b) is the functional module inside the modem. Signal conditioning for the receive hydrophone is accomplished by the analog processing board which has programmable input gain and band-pass filtering. The power amplifier board is used for amplify the modulated signal and matching with the transmitting transducer.

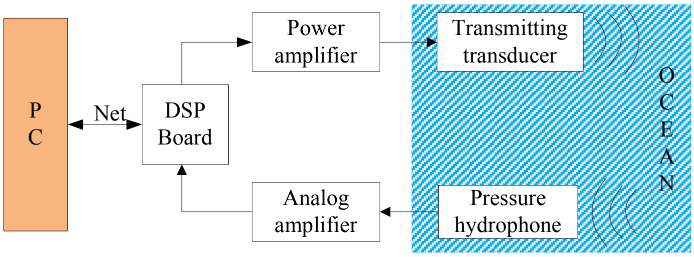
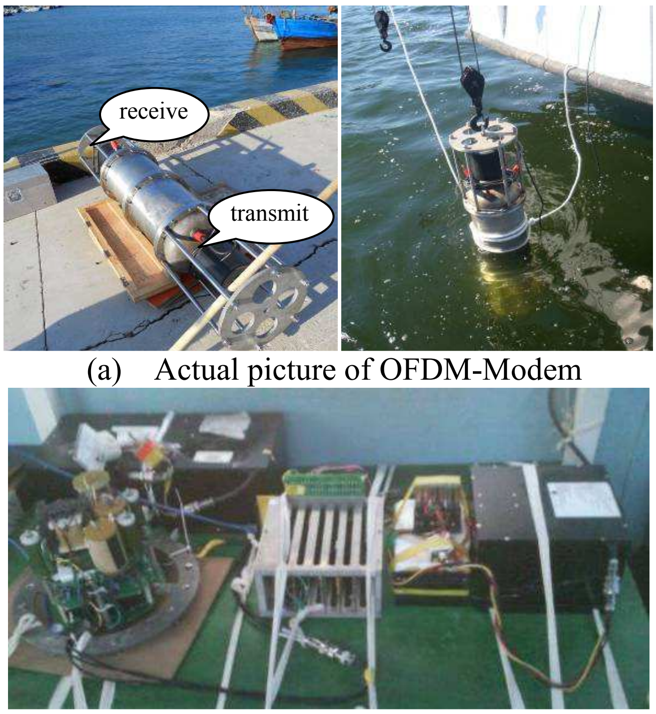


Fig. 3 Schematic of module connection



(a) Actual picture of OFDM-Modem

(b) Functional module of OFDM-Modem

Fig. 4 Actual picture of OFDM-Modem nodes

The DSP board in the OFDM-Modem is based on the Texas Instruments TMS320C6455 processor. This chip was selected for its high performance in additional with the dominant frequency being 1.2GHz, DDR capacity being 128 MBytes, FLASH capacity being 4 MBytes. Applying X4 series FPGA to realize the flexible logical control, data processing. AD adjustable sample rate can reach up to 1.25 MHz. AD and DA are used to sample and generate OFDM signals. 10/100M ethernet interface is integrated on board, and the network is available to convey the OFDM modulation and demodulation parameter, original data and the demodulation result.

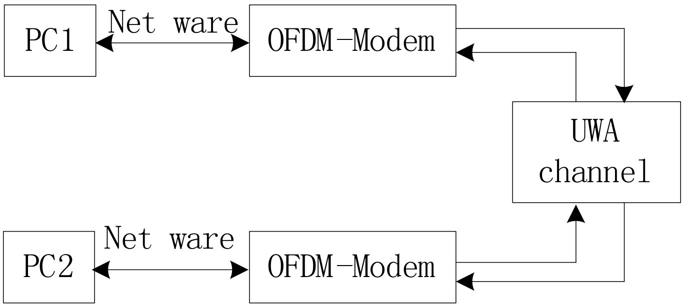
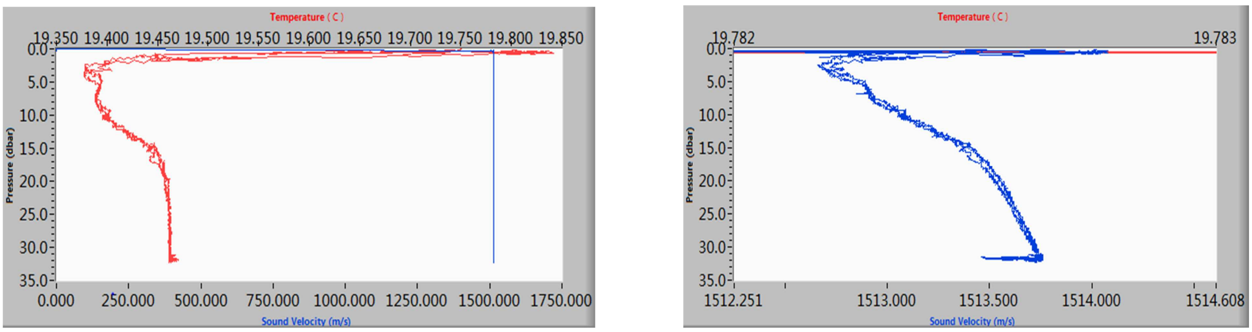


Fig. 5 Block diagram of OFDM-Modem UAC systems

Experiments and Results

Sea Trials. Although it can achieve the requirement of real-time communication and works well in the pool, We conducted an experiment in Yellow Sea near Dalian during 30th September to 6th November in 2011 to verify the performance of OFDM-Modem. The experiment block diagram is described in Fig. 5. The OFDM modem and laptop are connected by net ware. As the communication algorithm in this paper was still in the stage of prototype designing. Communication parameter in the system can be altered by net instead of solidification for convenience.

In the experiment, the transmitting ship and receiving ship kept stalling of engine，drifting on sea in a distance from 30km to 36 km because of the current and wind. During the communication period of 3 hours, the average speed of the ships was 1 knot, with a wave elevation of 0.5m - 1m. The OFDM-Modem modulate and transmit the OFDM signals when receive the order from PC. The OFDM-modem of receiving terminal process the received signals real-time, meanwhile, uploading and saving the demodulated result and original signal in the PC. The frequency band of the transmitting transducer is 3-10 kHz, receiving hydrophone is 3kHz-9kHz, and the depth of the sea water is 30 m. when the transmitting terminal and receiving terminal were in the distance of 36km, transmitting transducer and receiving hydrophone at a depth of 5 m in the sea. Sea water acoustic velocity gradient was measured by sound velocity gradiometer from company SeaCast. In Fig 6(a), the blue line represents the sea water acoustic velocity profile and the red one is sea water temperature. It is easily to figure out from the velocity profile map after partially enlarged in Fig.(b), The overall velocity variation is less than 2m/s. Sound rays were limited on the surface, and the transmission condition is well.



(a) Velocity profile map (b) Velocity profile map after partially enlarged

Fig. 6 Velocity measured in the experiment

Results. Because the transmission loss , the limitation of power amplifier and the high background noise, we get a signal with very low SNR in the distance of 36 km during the sea trial. Fig. 7 shows the waveform of time domain and frequency domain of OFDM signal receiving in the experiment using MATLAB. In time domain, we can see that the CW signal in the OFDM frame header waveform is relatively significant. However, the two signals LFM and OFDM near CW signal are totally submerged in the noises. In frequency domain, the CW signal with 3.5 kHz is clearly, while it is disturbed more in the low frequency of 1-3KHz and transmission loss more in the high frequency of 7-8kHz, it is easily to figure out that the shallow water with a channel of 36km has serious influence and low SNR because the frequency bandwidth of OFDM is 4-8kHz.

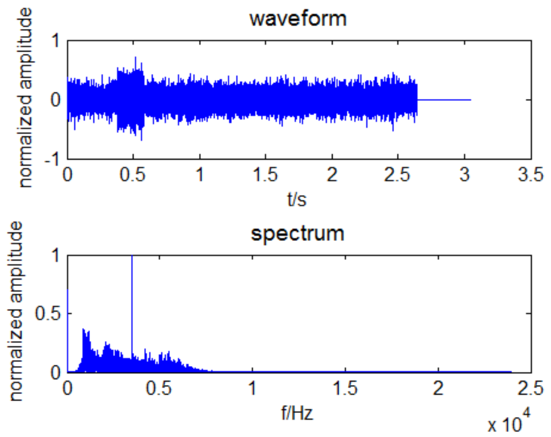


Fig. 7 Waveform and spectrum of OFDM of 36km

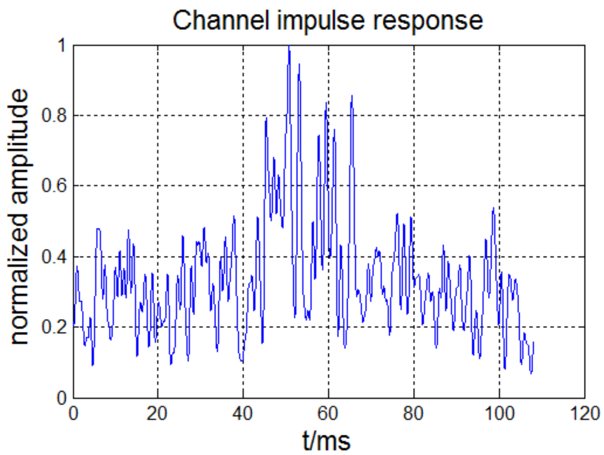


Fig. 8 Channel impulse response of 36km

Fig. 8 illustrates the channel impulse response which is measured by receiving LFM signal in the distance of 36m. In the figure we can't see the obvious multipath, though in the experiment day the scale of wind force reached 5-6 level. Because we can change the OFDM communication parameter freely via net ware, under the premise of the reliable communication, the spaces between comb pilot frequencies, length of pre-cycle and post-cycle, the number of frequency diversity and inserting the empty sub-carriers was changed to improve the performance in the experiment. There are 3 groups of parameter that can realize the robust communication in the distance over 30km after repeated validation. The parameters are shown in Table 1.

Table.1 Parameters of OFDM signal

Parameter	Parameter1	Parameter2	Parameter3
Sampling rate	48[kHz]	48[kHz]	48[kHz]
Signal bandwidth	4[kHz-8kHz]	4[kHz]-8[kHz]	4[kHz]-8[kHz]
Number of FFT	16384	16384	16384
Subcarrier spacing	2.93[Hz]	2.93[Hz]	2.93[Hz]
Circulating prefix	500	500	500
Circulating Postfix	0	0	0
Comb pilot interval	2	2	3
Number of diversity	3	2	2
Number of null subcarriers	4	2	2
Number of symbols per frame	5	5	5
Number of block pilots	1	1	1

Maximum Ratio Combining of frequency diversity is applied along with these three groups of parameters for OFDM communication system. For convolution code, coding rate is 1/2. The modulation format was QPSK. Analyzing from the DSP real-time demodulation statistic result is shown in Table 2, It can get the maximum communication speed of 426.4bps at the bit error rate of 10^{-3}. Meantime the underwater acoustic OFDM-Modem could realize long time robust communication in a long distance and low SNR environment.

Table.2 BER and data rate in the distance of 36km

Parameter	Original BER	Final BER	Communication Rate
Parameter 1	5.62%	0	213.2[bps]
Parameter 2	6.34%	0.023%	321.2[bps]
Parameter 3	5.83%	0.83%	426.4[bps]

Conclusion

We presented design, hardware implementation and testing of OFDM-Modem. The result of sea trial proved that OFDM-Modem can work real-time and reach the robust communication speed of 426bps in the distance of 36km.The next work is to optimize the algorithm and reduce program run time and power consumption. We will challenge the robust communication in longer distance, deeper sea and higher speed based on OFDM-Modem in the future.

Acknowledgment

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