Full-duplex, multi-user and parameter reconfigurable underwater acoustic communication modem

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***Abstract*—Underwater acoustic communication networks are becoming focus of active research due to several oceanographic developments and military applications. Long time delay present in underwater acoustic channel limits data rate of the network. Another major reason for low throughput is that almost all the acoustic modems operate under half-duplex mode. For increasing communication throughput, a full-duplex, multiuser, parameter reconfigurable underwater acoustic modem is presented in this paper. Transmission is done through an omnidirectional transducer and a directional vector sensor is used for reception. Orthogonal frequency-division multiplexing (OFDM) and Code division multiple access (CDMA) with spread spectrum (SS) are used for realizing full-duplex and multi-user acoustic communication. TMS320C6455 DSP and Cortex-A8 ARM are embedded in the modem for real time digital signal processing for the communication scheme. To cater different underwater environment conditions for some special applications, the parameters of OFDM can be modified via acoustic link using robust SS underwater acoustic communication. A cable link directly to the computer for modem parameter reconfiguration is also provided. The proposed modems have been tested in sea trials. The results of these trials indicate that significant improvement in the network throughput rate can be achieved by using above mentioned hardware and techniques.**

Keywords—underwater acoustic communication; modem; half duplex; multiuser; parameter reconfigurable

I. INTRODUCTION

Underwater acoustic communication networks have emerged as one of the exciting research area from the perspective of developments in ocean data collection. Acoustic modems are a key element in the underwater acoustic network as these are the nodes of any network. Many companies and research institutions have been actively engaged in the modem development.

Different requirements such as low power, low cost, compact size, high data rate, long-range transmission ability, high reliability or multiple access modes result in different designs and implementations for acoustic modems. Paper [1] describes a reconfigurable UWA modem which provides a flexible environment for the testing of different communication algorithms including networking protocols. [2] constructed an underwater acoustic modem using both frequency-hopping (FH) and direct sequence spread spectrum (DSSS) techniques. Quaternary frequency shift keying (4FSK) and differential binary phase shift keying (DBPSK) modulations were utilized in their solutions.

[3-7] focus on development of small size modem consuming low power. WHOI developed a Micro-Modem that is a compact, low-power acoustic transceiver. This can be used for acoustic telemetry and navigation purposes [3]. An Ultra-Low Power and compact Acoustic Modem is designed for Energy-Efficient Underwater Sensor Networks in [4,5]. The proposed solution uses coherent-FSK modulation and a combination of hardware and software that requires only 24 mW for receiving data. Moreover, with 108 mW of transmission power, the modem has been tested to transmit data upto 240 m range which implies an overall consumption of only 120 mW approximately. [6,7] developed a cylindrical shaped micro-modem that is only 70 mm in diameter and 35 mm in height without a transducer.

[8-11] focus development of modems with high data rate. Paper [8-9] describe a ultra-high data rate modem operating in two separate frequency bands. The high data rate uplink operates between 262 kHz and 375 kHz. The downlink is designed for lower data rate command-and-control signals and uses a lower frequency band (62-76 kHz). Both uplink and downlink have same source level. The acoustic uplink is capable of achieving data rates of 87768 bps. A high-rate modem which employs orthogonal frequency-division multiplexing (OFDM) scheme with a powerful forward error-correcting turbo block code for use in very-shallow water communications is proposed in [10]. Good performance in terms of bit error rate is achieved up to 1700 m for information rates of nearly 10 kbps. SISO and MIMO systems are realized with a floating point TMS320C6713 DSP development board in paper [11]. The data rates are 3.2 kb/s and 6.4 kb/s for SISO and MIMO systems respectively, with QPSK modulation, 1/2 rate channel coding and signal bandwidth of 6 kHz.

[12-13] try to develop a highly reliable modem. Paper [12] gives an adaptive underwater acoustic modem, which changes its parameters according to the environmental conditions for reliable and energy efficient communication in underwater sensor networks. A reliable underwater acoustic modem prototype design based M-ary chirp spread signals (MCSS) is presented in [13]. Error free communication to a distance of 212m and data rate of 300 bps was achieved with less than

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0.97 W transmission power in low SNR shallow water environment.

All the modems mentioned above have different features, but all these acoustic modems work under half-duplex mode which limits the net throughput rate. To achieve the objectives of high throughput rate, field reconfigurable and multiuser operation capable modem, we design and implement a full-duplex, multiuser and parameter reconfigurable acoustic modem. This full duplex capability assists in accelerating the initial setup configuration of the network also.

In the following section, we describe the proposed modem hardware and software architecture. Governing principles of vector sensor in underwater communication and the adopted algorithms are presented in section III. Experimental results of the sea trial of the system are given in section IV. Finally, in Section VI, we give a brief summary and comment on further works of this paper.

II. SYSTEM DESCRIPTION

A. Modem Overview

A full-duplex acoustic modem which can suppress local transmission interference consists of omnidirectional transducer, vector sensor, acoustic baffle and electronic components. Fig.1 gives the mechanical scheme and expected directivity of transmission and reception.

In order to suppress the local transmission interference we insert an acoustic baffle between transducer and vector sensor. These transducer and vector hydrophone are located on opposite sides of the modem. The acoustic baffle makes the transmission directivity pattern of the transducer cardioid as shown in Fig.1. For further suppress the effects of local transmission, receiver and transmitter are separated in space by a rod between the transducer and vector sensor in the vertical direction. We designed a scalable rod to make the assembly and transportation of the modem convenient.

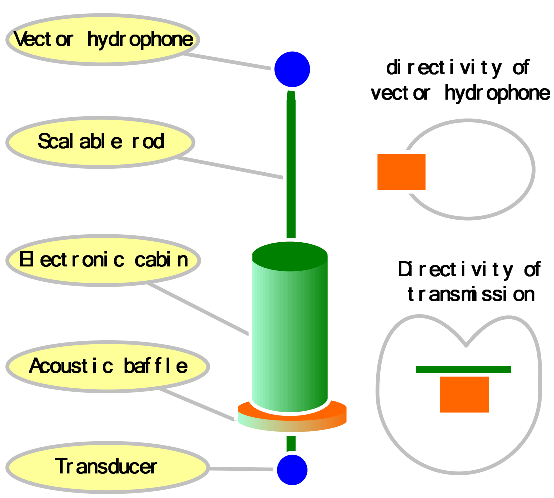

Fig. 1 mechanical scheme of full-duplex modem

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In addition to the above acoustic vector sensor used in this paper is capable of measuring two orthogonal particle velocity components and scalar acoustic pressure at a collocated point in space [14] simultaneously. This is also used for further local transmission interference suppression. In this paper, we point the null of the vector sensor's directivity pattern toward to the transducer to avoid its interference in reception. We also combine the vector signal to get higher SNR of the received signal[15].

These three measures are adopted to suppress the interference from the local transmission, improve SNR of received signal and achieve full-duplex underwater acoustic communication.

B. Electronic design

Fig. 2 gives the block diagram of the overall structure of our underwater acoustic full-duplex modem. The modem consists of two digital boards, a pre-amplifier board, a power amplifier board and a MSP430 main control board. All digital boards of the modem can be interconnected with external devices such as personal computer (PC) by a net switcher or hub.

A TMS320C6455 DSP board accomplishes the real-time digital signal processing for OFDM. TMS320C6455 is a high performance fixed-point DSP in the TMS320C6000 DSP platform with the main frequency 1.2GHz. It includes 10/100/1000 Ethernet media access controller (EMAC), which provides an efficient interface between the C6455 DSP core processor and the network [16].

S3C2440 ARM board is used for spread spectrum processing. The S3C2440A is developed with ARM920T core. Its low power consumption, simple and fully static design is particularly suitable for cost and power sensitive applications. S3C2440A maximum frequency is 400MHz [17].

For signal conditioning of the vector sensor, we design a reconfigurable signal conditioning board, which can amplify and filter one voltage signal from pressure sensor and two charge signals generated by the velocity sensor at the same time. The amplification gain and filter coefficients can be changed via the IIC bus.

The MSP430 main control board is used to configure the operating modes of the modem. In operating mode A, OFDM signal is modulated while SS signal is demodulated. Mode B is opposite to mode A. In this mode, transmitted signal is SS while received signal is OFDM. MPS430 board controls the Signal conditioning and power amplifier boards to work in either mode A or B.

The modem developed by the above mentioned design methodology is shown in Fig. 3. Fig. 4 shows the building blocks of this modem including DSP board, ARM board, MSP430 control board, front end conditioning board and power amplifier board.

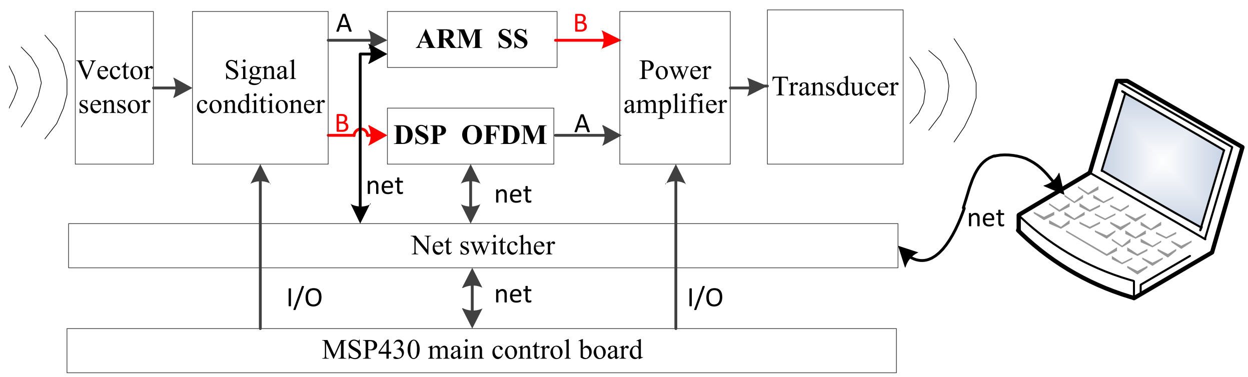


Fig. 2 Schematic of module connection

Fig. 3 actual picture of Vector-OFDM-Modem

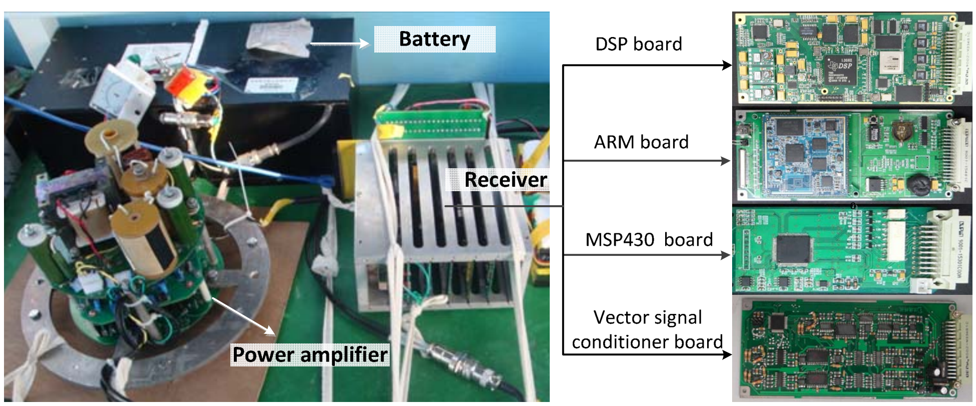


Fig. 4 electronic modules of the modem

III. Communication Algorithm

A. DOA estimation of vector sensor

Sound waves are characterized by compression and expansion of the medium as sound energy moves through it. This represents the pressure component of sound. At the same time, there is also back and forth motion of the particles making up the medium. Particle motion is described by displacement, velocity, and acceleration. A vector sensor can measure these vector components of the acoustic field such as the particle velocity. A single scalar sensor such as pressure hydrophone cannot obtain these.

Vector sensor installed in the full-duplex modem consists of an omnidirectional hydrophone that measures pressure and two particle motion sensors to measure the horizontal components of particle motion associated with the sound wave.

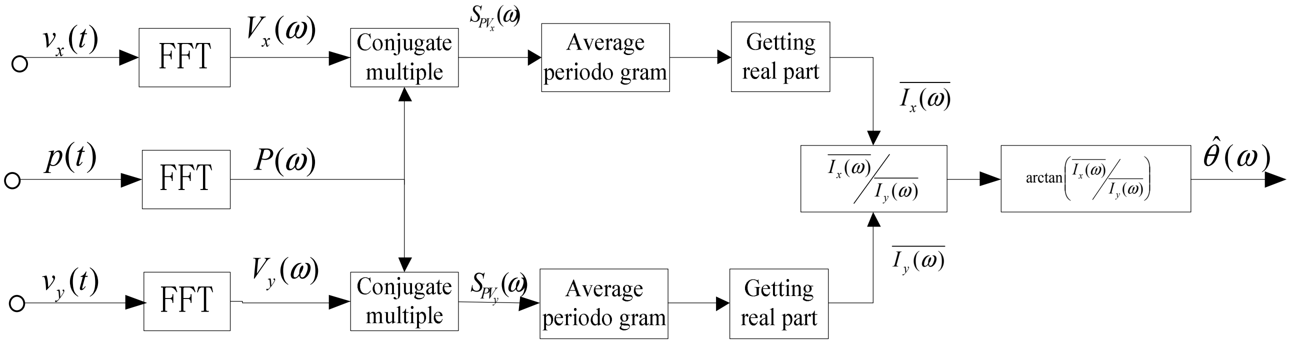


Fig. 5 direction estimation graph

Vector sensor can determine the direction in which a sound wave is traveling using measurements made at a single point in space. Due to more information of acoustic field obtained by vector sensor, joint processing of pressure and particle velocity was implemented for improving directivity gain of vector sensors in underwater acoustic communication. In addition, vector hydrophone could achieve space coherent interference suppression as well to improve the communication system performance. Direction estimation by data fusion of the pressure and velocity signals is introduced below. We adopt complex sound intensity method to estimate DOA (direction of arrival) of the received signal.

The complex sound intensity method is applied to realize the signal source direction estimating, the whole process is shown in Fig. 5. Fourier transformation is applied to the output of hydrophone, and then the frequency spectrum of sound pressure and oscillating velocity can be achieved. The target's energy focuses on the real part of the complex sound intensity cross spectrum output, while the interference energy mainly composes the imaginary part. Accordingly the estimate $\hat{\theta}$ of the target horizontal direction θ is:

$$\hat{\theta}(\omega) = \arctan \frac{\mathrm{Re}\left\{\overline{P(\omega)V_y^*(\omega)}\right\}}{\mathrm{Re}\left\{\overline{P(\omega)V_x^*(\omega)}\right\}} \tag{1}$$

The transverse line in the formula indicates the sliding window average periodical graph, and the direction of every frequency could be calculated according to the formula (1), and then the sound source direction could be estimated by weighted histogram method. According to the estimated direction and combined directivity of the electronically steered vector hydrophone, the main maximum direction will be steered to the sound source, and thus directivity gain will be used. Through the electronic steering combined directivities v_c and v_s of the velocity sensor are:

$$\begin{cases} v_c(t) = v_x \cos\varphi + v_y \sin\varphi = x(t)\cos(\theta - \varphi) \\ v_s(t) = -v_x \sin\varphi + v_y \cos\varphi = x(t)\sin(\theta - \varphi) \end{cases} \tag{2}$$

Where φ is the steering direction. The sound pressure signal is combined to the velocity signal in accordance with P+V, in this way we can write:

$$\begin{cases} p(t) + v_c(t) = 2x(t)\cos^2 \dfrac{\theta - \varphi}{2} \\ p(t) + v_s(t) = 2x(t)(\sin\dfrac{\theta - \varphi}{2} + \cos\dfrac{\theta - \varphi}{2})^2 \end{cases} \tag{3}$$

It can be seen from the formula (3) that both of them are single side directivity, and the directivity maximum point of $p + v_c$ points at the steering direction φ , whose directivity null point directs at the direction $\varphi + 180^\circ$; while the directivity of $p + v_s$ could be regarded as the directivity of $p + v_c$ rotated 90°anticlockwise.

B. OFDM

Fig. 6 gives the frame structure of Orthogonal Frequency Division Multiplexing (OFDM). The frame consists of two parts: synchronization signal and OFDM data signal. The frame synchronization signal has a structure of 2 LFM and 1 CW signal. The data may contain one or several OFDM signs. As multi-path response of the channel may lead to inter-channel and inter symbol interference of the OFDM signal, initial information could not be demodulated correctly. The paper applies the method of adding cyclic prefix and suffix to resist the multi paths influence, the structure of the OFDM signs are shown in Fig. 7.

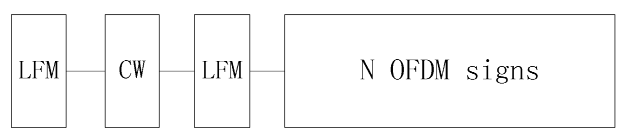


Fig. 6 Schematic of OFDM frame structure

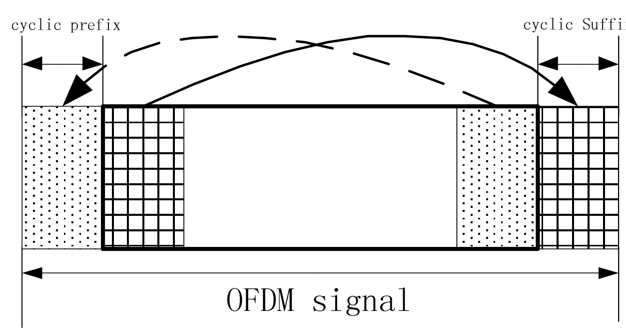


Fig. 7 Schematic of OFDM symbol structure

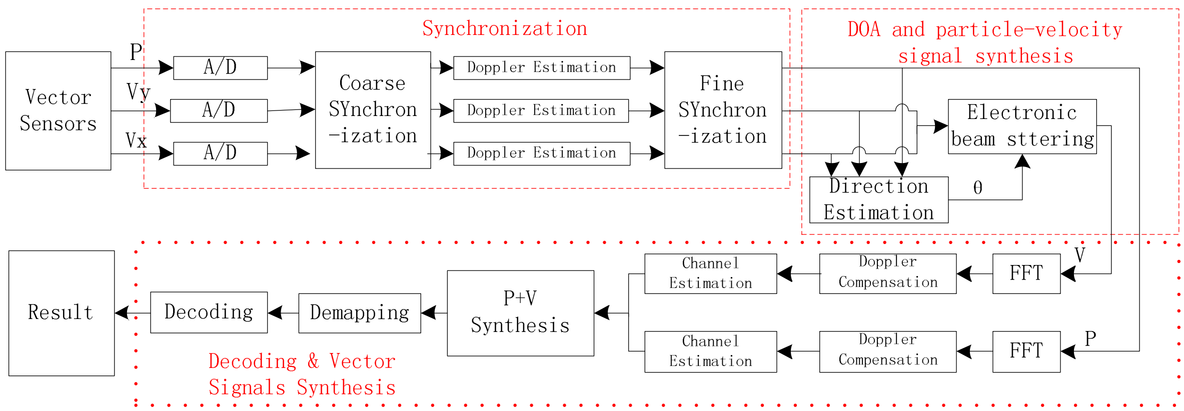


Fig. 8 Flow chart of vector signal processing

This section will introduce the demodulation algorithm of vector OFDM in detail. Taking into account the real processing capacity of the modem hardware, the processing flow of vector signals received is as Fig. 8 shows.

1) Synchronization

As Fig. 8 frame header shows, coarse synchronization, and fine synchronization are applied due to good autocorrelation and anti-multipath capability of linear frequency modulation signals. The so-called coarse synchronization indicates correlating local and received LFM to get a timing result, while the fine synchronization indicates correlating a local LFM and received LFM , which is influenced by Doppler, to get a signal timing. Signal synchronization and timing are achieved according to certain detection criterions. The first LFM signal of frame header is used for coarse synchronization, and the middle CW-frequency signal is used for detecting Doppler factor, while the second LFM is used for fine synchronization.

2) Signal source direction estimating and data fusion.

Applying the method demonstrated in Section 3.1, Signal source direction estimating and vector hydrophone data fusion can be achieved in the light of formula 1-2.

3) Doppler frequency shift compensation.

The method given in [11] of reference literature is applied to realize Doppler compensation. We use method of fitting FFT and parabola to detect the frequency of the CW-frequency signal to get the Doppler compressibility factor.

4) Channel estimation.

The channel estimation adopts a method based on Pilot Symbol Assisted Modulation (PSAM). According to our experience, the performance of block-type pilot will decrease with the passage of time. The comb-type pilot functions are not effective for narrow bandwidth of underwater acoustic channel. For these reasons, our system adopts a scheme that combines block-type pilot with low-density comb-type pilot.

C. DSSS underwater acoustic communication telemetry

1) Design of transmit signal

The synchronization signal and data stream are transmitted together in DSSS system in this paper, which can accomplish the initial measurement of channel parameters and track the channel status in communication. After synchronization, we know the number of propagation paths, and their respective delay along with weight and initial phase. We propose a quadrature modulation spread spectrum scheme as shown in Fig. 9. DSSS and code shift keying (CSK) spread spectrum are combined as a hybrid spread spectrum scheme, where the spread spectrum sequence is adopted to measure the channel characteristic in in-phase channel and data information is carried by code phase of sequence in quadrature channel.

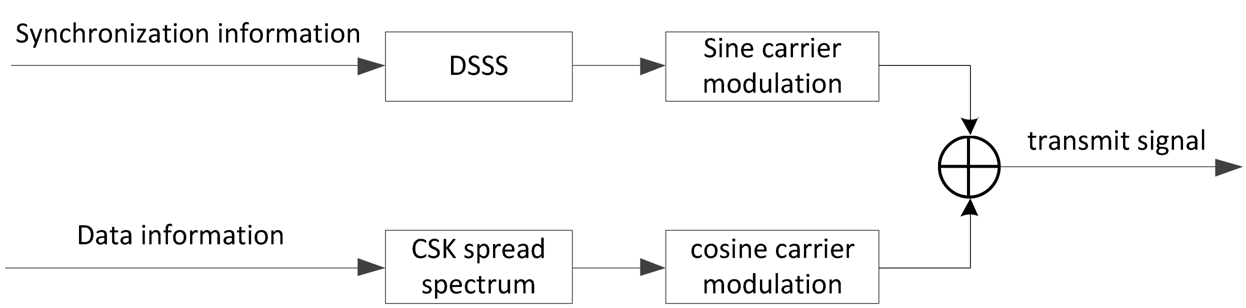


Fig. 9 The transmission block diagram

2) The Demodulation of the Receiving Signal

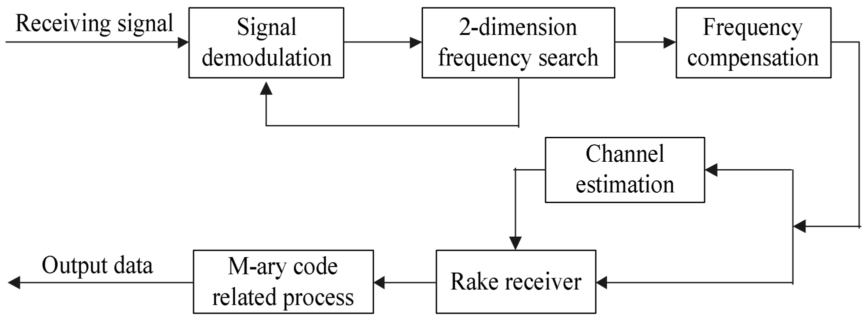


Fig. 10 The receiving block diagram

The receiving block diagram is shown in Fig. 10. At first, the received signal is subjected to a 2-dimension frequency search and synchronization process. After the coarse synchronization, accurate synchronization is performed. After the first process, the carrier frequency is compensated, and channel is estimated by using synchronization sequences. Then, the channel multipath signal are combined by Rake receiver with adaptive thresholds. Finally, the combined signal is processed by M-ary correlated process and data information is obtained.

The 2-dimension frequency search and synchronization process scheme of is given in the following Fig.11. The capture of carrier and code phase needs to be accomplished in synchronization process. The aim of this process is to reduce the error in phases of local code and received code to half code length. This also minimizes the difference in the frequency of received carrier and local carrier. The 2-dimention capture is shown in Fig. 8.

Rake receiver with adaptive threshold is designed. The threshold is set according to SNR. The advantage of this kind of Rake receiver is obvious in low SNR. The experiments have verified the gain of 2-3 dB coming from this method.

IV. Experiment Results

To evaluate the performance of the full-duplex modem, we conducted an experiment in Yellow Sea near Dalian, China. The modems and laptop are cable connected by ether net. The

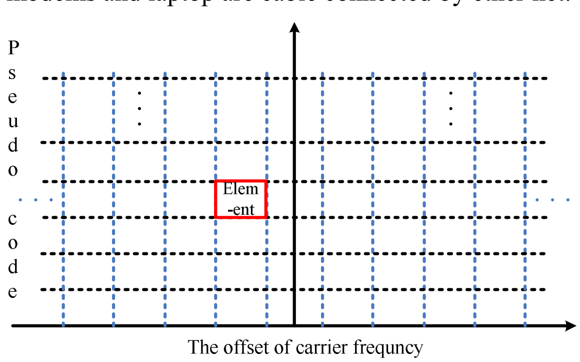


Fig. 11 The 2-dimension search figure of time and frequency

experimental setup of full-duplex and multiuser modem is shown in Fig. 12. Communication parameters in the system can be altered by net for according to operating modes and channel conditions. Modems numbered 1 and 2 operate under full-duplex mode (A) while modem 3 operated under multiuser mode(B). The average depth is about 20 meter and the modem depth is 5 meter from the surface.

The sound speed profile was measured by SeaCast sound velocity meter. In Fig. 13 (a), the blue line represents the sound speed profile and the red line is sea water temperature. It is easy to figure out from the sound speed profile (enlarged

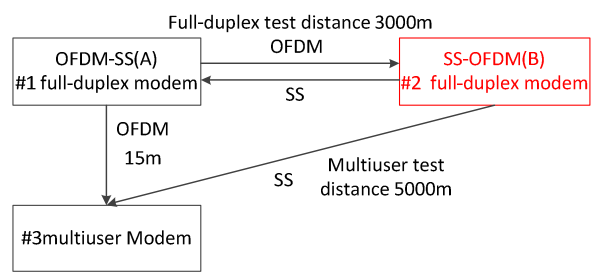
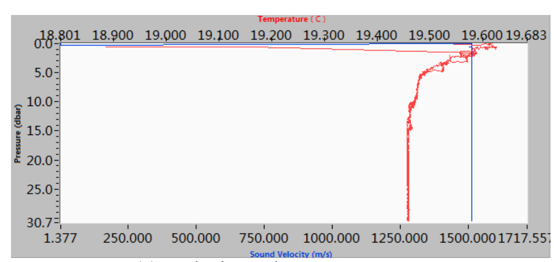
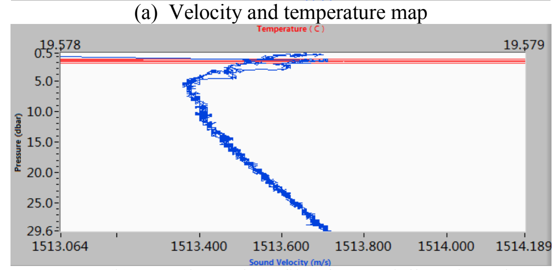


Fig. 12 modem deployed of full-duplex and multiuser modem



(a) Velocity and temperature map



(b) sound speed profile after partially enlarged

Fig. 13 sound speed profile in the experiment

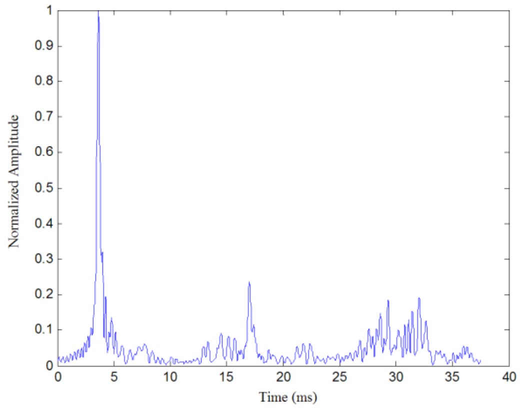


Fig. 14 channel impulse response

in Fig. 13 (b))that the overall velocity variation is less than 2m/s. Sound rays were confined to form a surface duct and the transmission conditions are good.

Channel impulse response (CIR) estimated by LFM in the preamble of OFDM signal is depicted in Fig.14. Here one can see that maximum delay spread of the channel is about 30ms.

A. *full-duplex mode results*

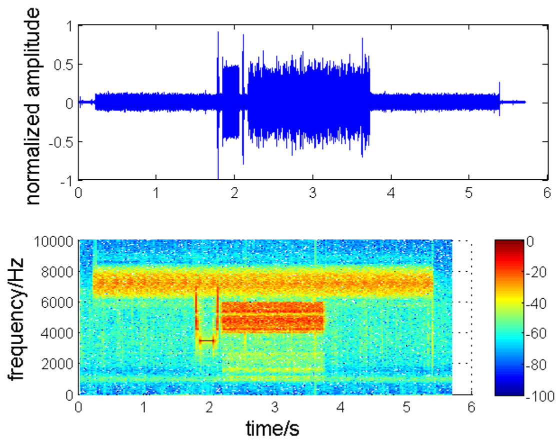


Fig. 15 modem signals for full-duplex mode OFDM-SS

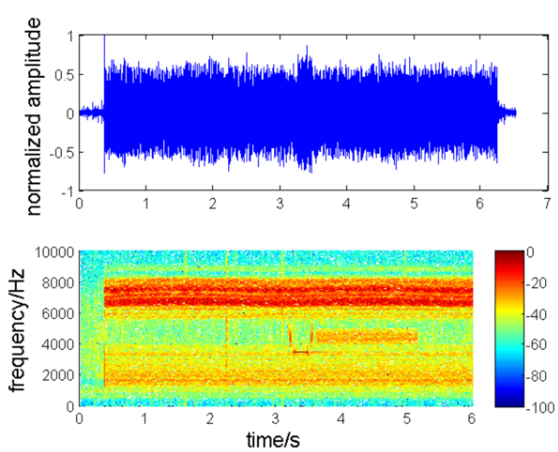


Fig. 16 modem signals for full-duplex mode SS-OFDM

In full-duplex mode， we put the transmitting and receiving modem both on the drifting ships. The ships are moving about 1m/s. OFDM is transmitted from modem number 1 to modem number 2, while SS is transmitted from modem number 2 to modem number 1. The data rate of OFDM is 710bps, SS is 10bps in the distance of 3km. The received OFDM and SS signal is shown in Fig.15.

In full-duplex mode， we put the transmitting and receiving modem both on the drifting ships. The ships are moving about 1m/s. OFDM is transmitted from modem number 1 to modem number 2, while SS is transmitted from modem number 2 to modem number 1. The data rate of OFDM is 710bps, SS is 10bps in the distance of 3km. The received OFDM and SS signal is shown in

Fig. 15 and Fig. 16. Error free transmission of both OFDM and SS is acomplished by manual configuration of modem parameter. Different SNR of OFDM and SS signals is needed because of difference in working principles of OFDM and SS to get same BER performance. We alter the parameter of OFDM and SS manually via the ether net to get error free result for both types of signals.

B. *multiuser mode results*

To evaluate the performance of multiuser modem, we configure modem 3 to work under multiuser mode which can receive OFDM and SS signal from modem 1 and 2 simultaneously. In this condition, data rate of OFDM and SS is 710 and 19bps respectively. Because OFDM needs higher SNR to get the same performance of SS, we put modem 1 which sends ODFM near modem3 with the distance of 15m. Modem 2 which sends SS signal is deployed far away from modem 1 and 2 with the distance of 5000m, the deployment of the three modems is shown in in Fig. 12. The received signal in the multiuser modem after vector combination is shown in Fig. 17. Though SS signal in the waveform of time domain is not visible, we can see the SS signal in the frequency domain in the range of 6 and 8kHz. Error free performance is also achieved via changing parameter of the communication algorithm.

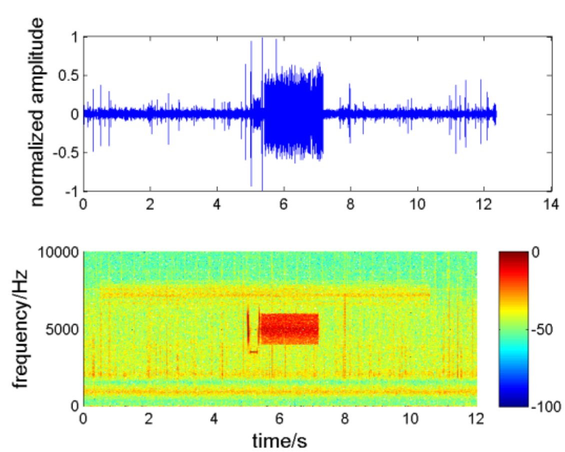


Fig. 17 modem signals received by multiuser modem

V. Conclusion

A full-duplex, multi-user and parameter reconfigurable acoustic modem is designed and implemented in this paper. The results of sea trial proved that the proposed modem can work real-time and reach good performance. The function of full-duplex is verified by two modems working under A and B mode respectively to a distance of 3km with data rate of OFDM and SS being 710 bps and 10 bps respectively. Multiuser operation is verified by using three modems simultaneously. The modem working under multiuser mode can demodulate simultaneous OFDM and SS signals from the other two modems. In this mode also, the data rate of OFDM is 710 bps and SS is 19 bps. In future, we shall optimize the communication algorithms to reduce program run time and power consumption. Our ultimate aim is to develop robust long range communication in deep sea with higher data rate based on the proposed modem hardware in the future.

Acknowledgments

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