Complementary Code Keying Modulation and Frequency Domain Equalization for Single-Carrier Underwater Acoustic Communications

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***Abstract*—In this paper, we investigate the single carrier modulation and detection schemes for underwater acoustic channel with relatively sever inter-symbol interference (ISI) and ocean ambient noise. Complementary code keying (CCK), a variation of M-ary Bi-Orthogonal Keying, is used as the modulation scheme. The CCK modulation with good auto-correlation and cross-correlation properties provides a strong tolerance to multipath distortion and supports high data rate transmission. For ISI mitigation, we propose the method of frequency domain equalization applied to single carrier solution. We present performance analysis on bit error rate (BER) for different detection schemes. The ocean experiment result shows that a reliable communication over 10 kilometers underwater transmission is achieved with a data rate at 4 kbit/s in 4 kHz of bandwidth.**

Keywords— complementary code keying (CCK); frequency domain equalization; single carrier; sparse channel estimation; underwater acoustic communication

I. INTRODUCTION

Over the past few decades, there have been a number of activities in the area of underwater acoustic communications. An underwater acoustic channel is characterized as a multipath propagation, frequency-selective fading, limited available bandwidth, and ambient ocean acoustic noise channel [1]. High data rate transmission in the underwater acoustic channel is very challenging [2]. It is generally recognized as one of the most difficult digital communication channel. In underwater acoustic communication, the long delay spread, which cause inter-symbol interference, may spoil tens or even hundreds of symbols. To obtain the high data rate and improve the performance of communication over band-limited acoustic channels, orthogonal frequency-division multiplex (OFDM) techniques have been applied as effective anti-multipath techniques to underwater acoustic communications [3][4]. OFDM can efficiently combat with inter-symbol interference and distortion caused by multipath propagation, and adapts simple Fast Fourier Transform (FFT) based equalization without complex time-domain equalization. However, high peak-to-average-power ration (PAPR) and sensitive to carrier frequency offset (CFO), which causes inter-carrier interference (ICI), are major drawbacks with OFDM system. An alternative to the OFDM approach, more traditional single carrier (SC) with advanced modulation and detection techniques has comparable performance and low complexity. SC system uses a single carrier, instead of multi-carriers in OFDM system. Therefore, the perk-to-average power is much lower for single carrier systems compared with OFDM systems.

In the realm of single-carrier, research work has been active on modulation and detection techniques. In this paper, we design a single-carrier underwater acoustic communication system using complementary code keying (CCK) modulation [5][6][7] and frequency domain equalization (FDE) techniques [8][9][10]. CCK modulation, which is adopted by IEEE 802.11b standard, with good auto-correlation and cross–correlation properties provides a strong tolerance to multipath distortion and supports high data rate transmission. Transmissions over long memory underwater acoustic channel, time domain equalization techniques are not efficient and the computational complexity is very high if channel impulse response has long length. Compared to time-domain equalization, SC-FDE has more attractive performance. Similar to OFDM, the frequency domain equalizer in SC communications is conducted block-by-block by performing FFT/IFFT operation. Hence, SC-FDE systems achieve the similar complexity and performance as OFDM systems.

The rest of the paper is organized as follows. In section II, we describe the system model of SC system using CCK and FDE techniques. In section III, we present experimental results in section VI. Finally, we draw conclusions in section V.

II. SYSTEM MODEL

In this section, we propose a CCK modulation technique that works in conjunction with frequency domain equalization for a single carrier underwater acoustic communication system.

A. CCK Modulation

Complementary Code Keying is developed by Intersil and Lucent Technologies and is adopted as the modulation scheme of the IEEE 802.11 Standard for high-rate spread-spectrum

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communications (5.5 and 11 Mbps) at 2.4 GHz band. In this paper, the CCK modulation scheme we use is based on 802.11 11Mbps mode.

CCK is an M-ary orthogonal keying modulation method where one of the M unique (almost orthogonal) signal code words are chosen for transmission. The CCK has a code length of eight. The eight-chip CCK code words are defined as follows:

$$C = e^{j\varphi_1}\left\{e^{j(\varphi_2+\varphi_3+\varphi_4)}, e^{j(\varphi_3+\varphi_4)}, e^{j(\varphi_2+\varphi_4)}, -e^{j\varphi_4}, e^{j(\varphi_2+\varphi_3)}, e^{j\varphi_3}, -e^{j\varphi_2}, 1\right\} \quad (1)$$

where C is the code word. As shown in (1), the CCK code word is determined by the four phase parameters φ_1, φ_2, φ_3, φ_4 and, where φ_1 is contained in all eight chips, φ_2 is contained in all the odd chips, φ_3 is contained in all odd pairs of chips, and φ_4 is contained in all odd quads of chips. To begin, the information bits are partitioned into 8-bit block as ($d_0, d_1, ..., d_7$). The eight bits encode the four phase parameters according to the scheme shown in Table I.

TABLE I. PHASE PARAMETERS ENCODING

Dibit	Phase parameter
$d_0 d_1$	φ_1
$d_2 d_3$	φ_2
$d_4 d_5$	φ_3
$d_6 d_7$	φ_4

The first two bits d_0 and d_1 encode the phase φ_1 based on differential quadrature phase shift keying (DQPSK) modulation as specified in Table II, i.e. the phase φ_1 is relative to the phase φ_1 in the previous symbol. The dibits (d_2 d_3), (d_4 d_5), and (d_6 d_7) encode the phase φ_2, φ_3, and φ_4 based on QPSK modulation, respectively, as shown in Table III.

TABLE II. DQPSK ENCODING

$d_0 d_1$	φ_1 of Even symbols	φ_1 of Odd symbols
00	0	π
01	$\pi/2$	$-\pi/2$
11	π	0
10	$-\pi/2$	$\pi/2$

TABLE III. QPSK ENCODING

Dibit ($d_i d_{i+1}$)	Phase
00	0
01	$\pi/2$
10	π
11	$-\pi/2$

In CCK, it takes 8 information bits to define each code word of an 8 complex chips. The 8 chips are QPSK symbols. Hence, there have $4^8 = 65536$ possible code words for 8 information bits. Actually, the CCK modulation chose $2^8 = 256$ code words from 65536 possible code words. With the larger set of good codes to pick, the CCK modulation provides a strong tolerance to multipath distortion due to the coding distance is large.

B. Frequency Domain Equalization

The frequency domain equalization in single carrier system makes use of the property of the fast Fourier transform (FFT) to design a block data structure. To perform the frequency domain equalization, the stream of transmit data symbols is partitioned into the block size of *N*. In generally, a guard interval of a length equal or greater to the duration of the channel impulse response is inserted at the beginning of each block. Moreover, the guard interval is often the repetition of last N_{cp} symbols of each block. It is so called cyclic prefix (CP). It eliminates the inter-symbol interference from the previous symbols, but also allows the linear convolution to be modelled as circular convolution when FFT operation is performed.

To develop the structure of the frequency domain equalizer, a block of signal $\mathbf{x} = [x_0, x_1, ..., x_{N-1}]^T$ is passed through a channel with the length of *L* impulse response $\mathbf{h} = [h_0, h_1, ..., h_{L-1}]^T$, where *T* represents the matrix transpose. It is assumed that the size of block *N* is larger than the length of channel impulse response *L*. For simplicity and without loss of generality, here, the channel time variation and channel noise are not considered. The received signal **y** is obtained by convolving **x** and the vector of the channel impulse response, **h**. It is written in a mathematical form as

$$\mathbf{y} = \mathbf{H}\mathbf{x} \quad (2)$$

Where **H** is a *N*-by-*N* circulant square matrix whose first column is given by the channel impulse response **h** with a number of zeros padding to the end to extend its length to the block size of *N*. According to the feature of circulant matrices, the circular matrix **H** can be diagonalized using fast Fourier Transform. Hence, **H** can be expressed as

$$\mathbf{H} = \mathbf{F}^{-1}\Lambda\mathbf{F} \quad (3)$$

Where **F** is the fast Fourier transform, $\mathbf{F}^{-1}$ is inverse fast Fourier transform, and Λ is the diagonal matrix whose eigenvalues are given by taking the fast Fourier transform of the first column of **H**. Substituting (3) in (2), we can obtain

$$\mathbf{x} = \mathbf{F}^{-1}\Lambda^{-1}\mathbf{F}\mathbf{y} \quad (4)$$

Therefore, the structure of frequency domain equalization in an SC system is similar to the time domain equalizer. The frequency domain equalization takes the FFT of each block **y**, multiplying the inverse of the elements of the FFT of the first column of H, and converting the results back to the time domain using IFFT operation.

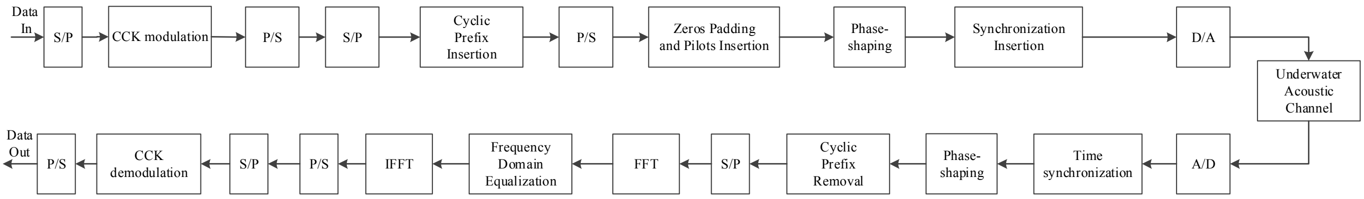

Fig. 1. Block diagram of an SC-FDE system enploying CCK modulation

C. SC-FDE System Model enploying CCK

The proposed single carrier system model employing CCK modulation and frequency domain equalization is depicted in Fig 1. The stream of input data is partitioned into 8-bit block through serial-to-parallel (S/P) conversion. Each 8-bit block is mapped into an 8 QPSK chip symbols by employing CCK modulation. The complex symbols undergo parallel-to-serial (P/S) conversion. Then, the serial symbols are partitioned into the block of N symbols, where N is the size of FFT. Each block is cyclically extended by copying the last N_{cp} symbols to the beginning of the block. After P/S conversion, the two identity training sequences, which are known to the receiver, are inserted in the front of data blocks. The length of training sequence is set to be at least equal to the length of channel impulse response, and it may be equal to or less than the length of a data block N, and it is often set to the power of 2. Two golden sequences are used as pilots. The golden sequence has attractive periodic autocorrelation property. The first golden sequence acts as CP that absorbs inter-symbol interference. The second golden sequence is used for channel estimation. After through the pulse-shaping filtering, the baseband signals are formed; then the baseband signals are modulated to desired frequency by multiplying the carrier signal. A chirp signal is inserted in front of the packet as a preamble, which is used for time synchronization. The packet structure is depicted in Fig. 2. The digital-to-analog (D/A) conversion and transducers produces the acoustic signal, which is transmitted over underwater acoustic channels.

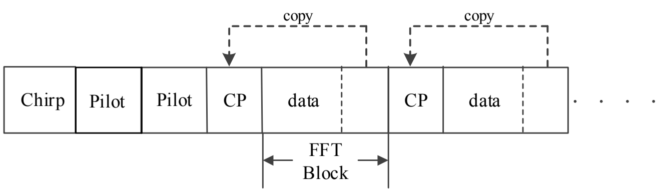

Fig. 2. Packet structure of SC-FDE

In the receiver, the signal at the output of the underwater acoustic channel undergoes transducer/hydrophone conversion, analog-to-digital (A/D) conversion, and frequency down conversion. The time synchronization finds the start of the transmitted signal, and produces a sequence of noisy symbols whose length is equal to the transmitted data block. The CP of each data block is discarded. The rest of the block is sent to the FFT which converts the complex time domain symbols into frequency domain. The Frequency domain equalization combats with inter-symbol interference. The output results of frequency domain equalization are converted back to the time domain. Finally, symbols-to-bits and data decision are made after CCK demodulation.

III. EXPERIMENT RESULTS

In this section, we present the results of the proposed CCK modulation and SC-FDE solution in the shallow underwater channels. The experimental data were collected off the Coast of Xiamen City, Fujian, China, in January 2015. As shown in Fig. 3, the distance between transmitter and receiver is 10 kilometers. In the transmitter, one transducer is deployed 9 meters beneath the ocean surface. The depth of water is 16 meters in the transmitter area. In the receiver, we arrange five transducers/hydrophones to receive the transmitted signals. Three transducers/hydrophones are deployed equally spaced 3 meters on a vertical linear array, and the deepest one is 9 meters underwater. The other two transducers/hydrophones are also deployed vertically with 4.5 meters underwater and 10.5 meters underwater, respectively. The depth of water is 20 meters in the receiver area. The data are collected through NI DAQ (NI USB-6259) connected to a computer for off-line processing.

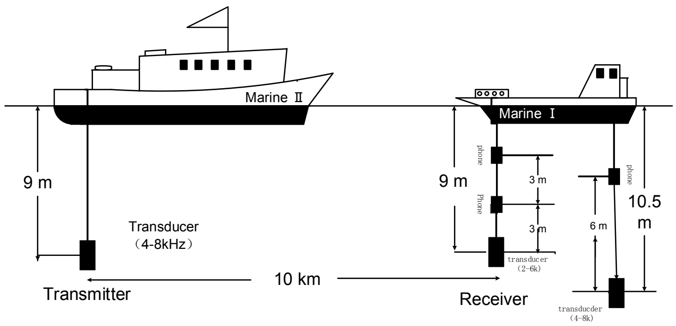

Fig. 3. The deployment of equipment

The experimental parameters are set as follows. The duration of every symbol is T_s = 0.5 ms. The sample rate is set to 60 kHz. The center frequency of carrier is 6 kHz. The frequency band range of transmitted signal is from 4 kHz to 8 kHz. The chirp signal lasts 2 seconds to make sure the accuracy of time synchronization. The training sequence is 512 bit golden sequence (appending a zero in the end). The data block size is N = 1024, and the length of CP is 256. Because of the uncontrolled conditions in the ocean, the time for experiments performing is very limited. The fig.4 is depicted the ocean experiment scene. In this experiment, the total number of data block sent is 8. For the CCK modulation, which is detailed discussed in section II, 8192 information bits are mapped to QPSK symbols. The transmission data rate is 4 kbps.

Fig. 4. The ocean experiment scene

For the channel estimation, we adopt the conventional Least-Square (LS) algorithm. We report bit error rate (BER) results for the three frequency domain equalization methods. They are Zero-force frequency domain equalization, LMS frequency domain equalization, and SC-FDE decision feedback equalizer (DFE) [8].

TABLE IV. AVERAGE BER OF SC-FDE EMPLOYING CCK

#Hydro -phones	Zero-force Equalization	LMS Equalization	DFE Equalization
1	3.61%	0	0
2	3.75%	0	0
3	42.94%	1.01%	0.4%
4	5.22%	0	0
5	21.4%	1.53%	0.21%

Table IV shows the average BER results for the three frequency domain equalizers. The first column is the tag of five hydrophones/transducers. With good channel condition, such as data collected from #1 hydrophone, #2 hydrophone, and #4 hydrophone, the SC-FDE system with LMS frequency equalization or DFE equalization can achieve zero error transmission (the minimum bit error rate is 1.2×10^{-4}). That means reliable underwater acoustic communications are obtained with data rate at 4 kbits/s in 4 kHz of bandwidth. The performance of DFE equalization is the best. Zero-force equalization performs the worst; sometimes it cannot eliminate channel distortion efficiently.

IV. CONCOLUTION

A novel CCK modulation and frequency domain equalization scheme has been presented for single carrier underwater acoustic communication system. CCK modulation supports high data rate transmission and has a good auto-correlation property, which provides a strong tolerance to channel distortion. The performance of SC-FDE system is similar to that of OFDM, even with a long memory channel. Meanwhile, the complexity is reduced compared to time domain equalization. The practical ocean experimental results demonstrated that an SC-FDE system employing CCK modulation achieves a robust underwater acoustic communication. The bit error rate is below 10^{-4} with data rate at 4 kbits/s in 4 kHz of bandwidth.

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