Research on Base-Band OFDM Underwater Acoustic Communication System

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Abstract—It is tough to achieve higher transmit speed and lower bit error rate(BER) because of the complexity of the underwater acoustic channel. This paper proposes a method of orthogonal frequency division multiplexing (OFDM) modulation technique for improving the situation. It can reduce BER with the ability of resisting multi-path interference and can increase communication rate with the characteristic of parallel multi-carrier transmission. The system on underwater acoustic channel proposed in this paper is a base-band system. It can simplify the structure of receiver and reduce the requirement of carrier frequency synchronization. It can improve the system reliability by choosing the appropriate length of OFDM symbol and using frequency diversity method. We perform the experiments in the very shallow waters with depth of 6 meters and the distance between transmitter and receiver is 1km. The experiment results show that the BER is less than 10e-5 and the transmission rate is greater than 1kbps.

Keywords-underwater acoustic communication, frequency diversity, OFDM , base-band

I. INTRODUCTION

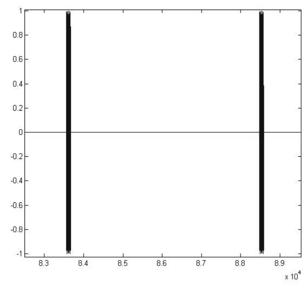
Water channel is an extremely complicated multi-path transmission channel with random parameters of time, space and frequency. There are high ambient noise and large time delay in this bandlimited channel. These unfavorable factors exacerbate the difficulty to reduce the multipath interference in water communication system. The underwater acoustic communication system of using frequency-hopping techniques has been proven to be a reliable data transmission in bad channel acoustic environment. However, the shortcoming of a robust frequency-hopping communication system is the low data transmission rate which is less than 100bps.

Orthogonal frequency division multiplexing (OFDM) is a multi-carrier modulation technique which is deemed to be an effective technology to resist multi-path interference. In recent years, the research of OFDM technique applied in underwater data transmission has become the world's hot spot, many experiments were carried out in different waters, such as Singapore Waters, Buzzards Bay in south-east of America, Woods Hole harbour in Cape Cod of Massachusetts of America, Baltic Sea La Ciotat in France and Songhua Lake, Qiandao Lake in China which are Inland lakes. The results of the OFDM underwater acoustic communication systems show that transmission rate is up more than 1 kbps when the bit error rate is less than 10^{-3}.

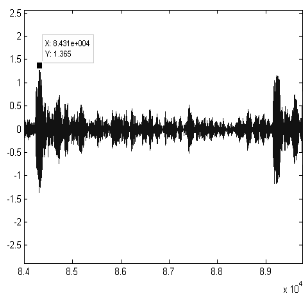
In this paper, we build a robust OFDM underwater acoustic communication system with high reliability and simple realization. A number of experiments are performed in a very shallow sea with depth of 6 meters in Xiamen. The results in statistics show that at a distance of 1 km, without channel coding, the bit error rate is less than 10^{-5} and transmission rate is greater than 1kbps.

II. FADING ANALYSIS OF UDERWATER ACOUSTIC CHANNEL

In shallow water, there are a large numbers of acoustic paths between transmitter and receiver due to refracting, reflecting and scattering and so on, which cause serious multi-path propagation effect. A sample of time domain experimental signal in shallow water is shown in Fig. 1. The signal of 14kHz frequency lasting 10 cycles is shown in Fig.1 (a) and the interval of the signal is 100ms. The received signal affected by multi-path propagation is shown in Fig.2 (b). We can see that there are lots of multi-path signals between interval of the signal.



(a)



(b)

Fig.1. Multi-path effect in shallow water
(a) Sending single-frequency signal of 14 kHz
(b) Received single-frequency signal of 14 kHz

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Signals transmitted from underwater acoustic multi-path will add together at the reciver. The signal amplitude will be enhanced if the phases of those signals are the same, and will be weakened if they have opposite phases. Thus, the envelope of the signal will be rapidly changed and the fading will take place. Digital signal of different bandwidth will be influenced differently by multi-path propagation. Let digital signal of limited frequency band to do orthogonal frequency expansion, it is represented by

$$x(t)=\sum_{k=k_1}^{k=k_2} C_k \cos(kw_0 t+\Phi_k) \tag{1}$$

Where $w_0=\frac{2\pi}{T}$, T is the period of the signal The system's bandwidth is $F=\frac{k_2-k_1+1}{T}$. Ignoring the additive white Gaussian noise (AWGN) and propagation time, The received multi-path signal is represented by

$$\begin{aligned} y(t) &= \sum_{i=1}^{m} u_i \sum_{k=k_1}^{k=k_2} C_k \cos[kw_0(t-\Delta t_{ik})+\Phi_k] \\ &= \sum_{i=1}^{m} u_i \sum_{k=k_1}^{k=k_2} C_k \cos[kw_0 t+\Phi_k+\varphi_{ik}] \end{aligned} \tag{2}$$

Where u_i and Δt_{ik} can be expressed as the transmission attenuation coefficient and delay time for **i**th path in all m paths. Phase is $\varphi_{ik}=kw_0\Delta t_{ik}=\frac{2\pi}{T}k\Delta t_{ik}$. $\Delta t_{\max}$ is the maximum multi-path delay. If signals with different bandwidth are sent, the received signals will show different fading characteristics.

On one hand, if bandwidth is much less than the reciprocal of the maximum multi-path delay, that is $F<<\frac{1}{\Delta t_{\max}}$ .It represents the conditions that signal bandwidth is relatively narrow or propagation delay is relatively short, in which situation the phase of the signal is $\varphi_{ik}\in(\frac{2\pi}{T}k_1\Delta t_{\max},\frac{2\pi}{T}k_2\Delta t_{\max})$,and $2\pi F\Delta t_{\max}<<2\pi$ is valid. Since it can be assumed that φ_{ik} and k are independent of each other, that is $\varphi_{ik}=\varphi_i$. (2) can be denoted as

$$y(t)=u\sum_{k=k_1}^{k_2} C_k \cos[kw_0 t+\Phi_k+\theta] \tag{3}$$

Where u is the envelope with Rayleigh distribution, θ is the phase with uniform distribution. The water channel is assumed as a flat fading channel.

On the other hand, if bandwidth and the reciprocal of maximum of multi-path delay are equivalent. It represents the conditions that the signal bandwidth is relatively wide or propagation delay is relatively long, with signal's phase φ_{ik} not only relevant to i, but also relevant to k. (2) can be denoted as

$$y(t)=\sum_{k=k_1}^{k_2} C_k u_k \cos[kw_0 t+\Phi_k+\theta_k] \tag{4}$$

The different frequency components of the received signals have different transmission attenuation coefficient u_k and phase θ_k . The channel shows frequency selective fading with spectrum distortion, and causes inter-symbol interference.

Analysis given above shows that under multi-path environment, there may be flat fading and frequency selective fading when sending signal's bandwidth changes from narrow to wide. Under certain band-width conditions, one of the two kinds of fading is much stronger than the other. But either fading will cause bit errors and decrease the reliability of underwater communication system. Because of multi-path signals and the sending signal are not independent of each other, it can not be overcame by using frequency filter or adjusting transmission power. Following are some of the ways to enhance the performance of the system:

Directional transducer or transducer array are used to reduce the numbers of the multi-path arriving at the receiver.

Adaptive equalization technique which can track the channel's changes and adjust the parameters of receiver adaptively are used, the fading of the signal will be compensated.

A communication system are designed to overcome the fading, including selection of transmission source, modulation and detect techniques.

The first method mentioned above not only increases complexity of the equipments, but also impacts the operability and convenience of the communication system. The second one requires strictly for the implementation of adaptive equalization technique because of the rapid time-varying characteristics of the underwater channel. However, the third method is a relatively feasible one. This paper presents a new anti-fading method which use OFDM as modulation and demodulation scheme to resist frequency selective fading and use frequency diversity technique to resist flat fading.

III. OFDM MULTI-CARRIER MODULATION TECHNIQUE

OFDM technique divides the transmission channel into a number of orthogonal sub-channels and the bandwidth of each sub-channel is less than the coherence bandwidth of underwater channel, which is the reciprocal of maximum multi-path delay. From the analysis of II part, each independent sub-channel can suppress frequency selective fading and possesses flat fading characteristics. However, OFDM is a kind of multi-carrier signal and due to the dispersion of power, some sub-carriers in random are featured with deep fading characteristics inevitably. Experiments in reference [5] show that frequency diversity is an effective method to suppress deep fading.

Therefore, the key techniques of underwater acoustic communication system based on OFDM are as follows:

First is the symbol length selection. Symbol length corresponds to signal period. The longer is signal period, the stronger to combat multi-path interference. Because the increase of symbol length will influence the communication bit rates. The selection of symbol length plays a very crucial role in the design of the system.

Second is the frequency diversity implementation. In OFDM communication system, the implementation contains frequency distribution in transmitter and combined method selection in receiver.

Finally is base-band system implementation. OFDM system has unique synchronization structure of three-level: carrier synchronization, sample synchronization and symbol synchronization. And OFDM is very sensitive to carrier synchronization. Kinds of factors in the system will result in carrier frequency offset (CFO), which will cause high BER. So, if the carrier modulator is not used in the transmitter, not only the transmitter structure is simplified, but also the system performance decrease problem brought by non-synchronization is eliminated. Base on this consideration, OFDM base-band system implementation is a key step too.

A. Implementation of Base-band System

OFDM is modulated by a group of different sub-carries. Let $s(t)$ be OFDM modulated signal:

$$s(t) = \sum_{n=0}^{N-1} x(n) e^{j2\pi n \Delta f t} \qquad 0 \le t \le T \tag{5}$$

Where, $x(n)$ represents the parallel transfer data. Δf represents the sub-carrier interval. If OFDM modulated signal is sampled by the interval $\frac{T}{N}$, that is $t = \frac{kT}{N}(k = 0,1,\cdots,N-1)$. According to (5), we can get:

$$s_k = s(kT/N) = \sum_{n=0}^{N-1} x(n) e^{j\frac{2\pi nk}{N}} \qquad (0 \le k \le N-1) \tag{6}$$

Where, the orthogonal condition $T = 1/\Delta f$ has been substituted in (5).

Equation (6) is equivalent to IDFT operation of $x(n)$, which can be implemented by IFFT. The analysis in receiver is similar to transmitter, which can be implemented by FFT.

Base-band OFDM can be implemented by carrier mapping. Let f_h and f_l be maximum and minimum frequency and system bandwidth is $B = f_h - f_l$. The information sequence is mapped to L complex sequence $\{X_0, X_1, \cdots, X_{L-1}\}$, where L satisfies $\Delta f \times L \le B$. Through some special processing of the above complex sequence, the transmitted data sequence $X[k]$ is formed. And N dots IFFT transform of $X[k]$ is performed, finally the time sequence $\{x_0, x_1, \cdots, x_{N-1}\}$ of the OFDM symbol can be get and transmitted.

B. Frequency Diversity

Frequency diversity refers to modulate a signal with two or more frequencies at the same time. As long as the frequency interval is large enough so that signals of different frequencies have the sub-independence of fading. And they are combined in a certain way in the receiver, the anti-fading effect can be improved due to the compensation between signals of different frequencies.

Frequency diversity Implementation in base-band OFDM system is that each signal is mapped into multi-carriers of different frequencies. The frequency interval should be greater than coherence bandwidth to ensure the independence of the frequency fading. In fact, diversity effects are obvious when the frequency interval is about hundreds of Hz. Different symbol mappings in transmitter have different combination methods in the receiver. For differential mapping signal, equal gain diversity combining is used after demodulation. For non-differential mapping signal, selective combination, feedback combination, maximum ratio combination and equal-gain combination etc can be used before demodulation.

A block diagram of the communication system is shown in Fig.2.

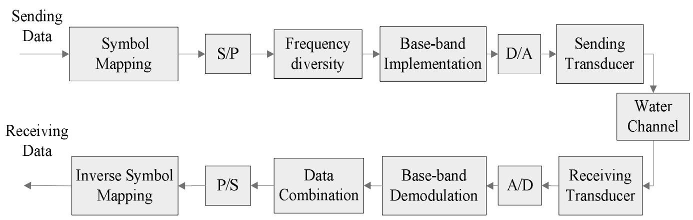

Fig.2.The simplified block diagram of the base-band OFDM system

IV. EXPERIMENTAL RESULTS

A number of experiments in Wu Yuan Bay in Xiamen, which is shallow bay are performed in 2008. The depth of the sea water changes between 4 and 8 meters depending on the tide. Seabed is a mixed media of sludge, rocks and sand. Sailing boat activity is frequent on the sea that is Olympic Games sailing boat training base. The sea waves are not big and there is spray occasionally. In general, the experimental area of underwater acoustic channel conditions is relatively poor, severe attenuation, multi-path interference and environmental noise. The experiments are performed on the wooden plank road extended to the bay in coast. The position of transducers is shown in Fig.3. The straight-line distance between the transmitter and the receiver is 1 km. Sending instantaneous power is 20W and water depth is 6 meters. The depth between transducer and seabed is 3 meters.

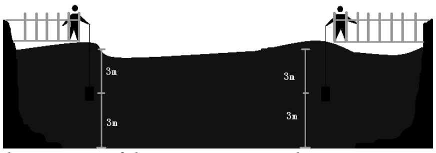

Fig.3 the position of the transmitting and receiving transducers

The block diagram of the OFDM system is shown in Fig.4.

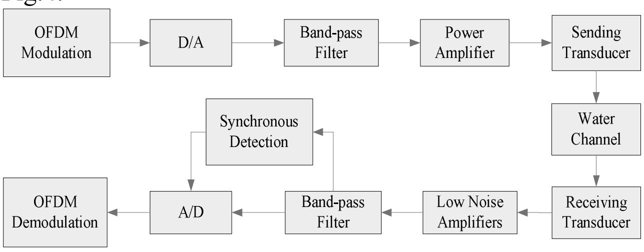

Fig.4 The block diagram of the OFDM system

The work band of the OFDM system proposed in the paper is 13 kHz to 18 kHz. Occupied Bandwidth is 5 kHz. The experimental data show that the fading of signal with time and frequency variability. It is shown in Fig. 5.

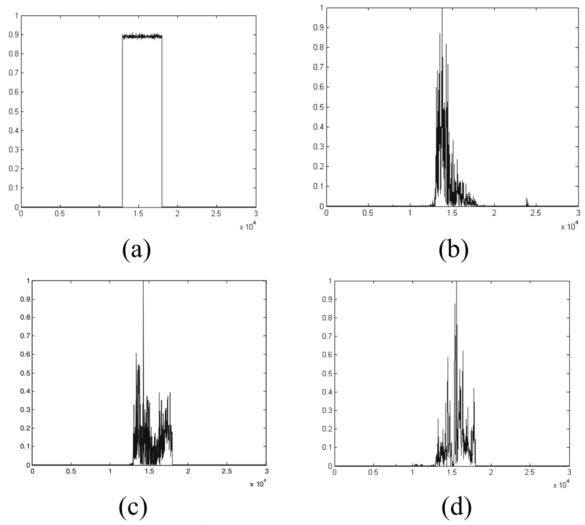

Fig.5 Random changes in frequency fading. (a) is the frequency spectrum of transmitted signal,(b),(c),(d) are three samples of frequency spectrum of received signal.

For comparison, we can use two methods to build a base-band OFDM system by modifying the OFDM symbol length or whether to use frequency diversity. The results are shown as follows.

TABLE I. TABLE TYPE STYLES

	Parameter Settings		BER	Effective Transmission Rate
	Symbol Length (ms)	Frequency Diversity		
System 1	21	No	5*10e-2	7.4 kbps
System 2	85	No	3.6*10e-3	7.4 kbps
System 3	85	Yes	7.6*1e-6	1.5 kbps

From these experimental results, we observe that the proposed system in this paper works better and increases the reliability of data transmission, which reduces the bit error rate by nearly three orders of magnitude. In today's case, moreover, the transmission rate of underwater acoustic communication is only a few hundred bps. Communication rate which is 1.5 kbps shows a considerable advantage.

V. CONCLUSION

In very shallow waters, multi-path effects of the water channel are obvious. The received signal shows the flat fading or frequency selective fading characteristics depending upon the band width of sending signal. This paper established an base-band OFDM communication system combining with frequency diversity methods. Proper symbol length of the OFDM signal are chosen to reduce the ISI of the underwater channel. The results show that this OFDM underwater acoustic communication system is robust, reliable and high-speed.

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