# High-Speed Underwater Acoustic Communication Based on OFDM

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**Abstract:** Due to multipath propagation and frequency selective fading, there are many obstacles for reliable and high data rate underwater acoustic (UWA) communication. OFDM is an attractive technique beginning used in UWA communication with three obvious advantages: good performance against multipath interference, ability to combat the frequency selective fading and the high frequency band efficiency. Recently, the researches of Refs.1, 2, 3, 4, 5 focus on short-range UWA communication. In this paper, we pay attention to medium-range (10 km) UWA communication based on OFDM. An OFDM system is designed and realized. Several important problems are described in which the characteristics of UWA channel is analyzed, Doppler frequency shift is estimated by using cyclic prefix and compensated by resampling the received signal. Experiments in a lake were conducted and its performance is investigated. Experimental results show that the data rate reach 9kbps and 2.8kbps at a distance of 5km and 10km respectively with the bit error rate (BER) below $10^{-4}$.

**Keywords:** OFDM, Underwater acoustic communication, Doppler compensation, Lake experiments

## 1. Introduction

Orthogonal frequency division multiplexing (OFDM), one kind of multi-carrier modulation, as one charming technique for future wireless application, has high bandwidth efficiency and the advantages of combating the frequency select fading. In OFDM system, intersymbol interference (ISI) introduced by multipath propagation, which is very popular in underwater acoustic (UWA) channel, can be removed by using guard time. For these reasons, OFDM has been used in high-speed UWA communication recently [1-4]. The first application system [1], which applied DFT based filter banks, was used in 1.9 km, a short-range channel; however, the effective data rate is only 250 bps. A new coherent COFDM system is proposed which uses a special form of pseudo-random phase modulated OFDM signal [2]. In order to improve the performance of the system, a frequency domain coded decision feedback equalizer was introduced; and only simulation results were given. The parameters of an OFDM system for broadband UWA communications were presented, such as design criteria, analysis procedures and simulation results [3]. A preliminary analysis of data from a sea trail showed that the data rate was 4400bps at a range of 1.2km by using OFDM [4]. However, these systems were designed for UWA communication at a distance of about 1km. In order to extent the OFDM to medium-range UWA communication, we design an OFDM system for 10 km range UWA communication and investigation its performance. We also conduct an experiment in a lake. The experimental results show that the data rate reach 9kbps and 2.8kbps at a distance of 5km and 10km, respectively, with the bit error rate (BER) below $10^{-4}$.

## 2. The characteristics of underwater acoustic channel

### 2.1 Bandwidth

The frequency bandwidth of an UWA

communication system is determined by frequency dependent transmission loss, ambient noise and range. Usually, the bandwidth of this system ranging about 10 km is only few kHz.

## 2.2 Multipath

Within the limited bandwidth, the signal is subject to multipath propagation through underwater channel. Multipath propagation causes ISI which restricts the data throughputs and degrades the system performance. For this reason, the UWA channel impulse response is represented by

$$h(\tau;t)=\sum_{i}\alpha_i(t)\delta[\tau-\tau_i(t)] \tag{1}$$

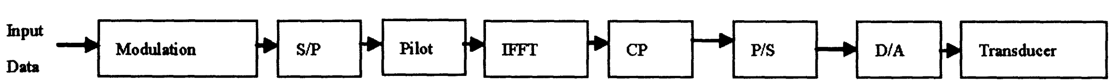
in which, both $\tau_i(t)$ and $\alpha_i(t)$ can be expressed as random processes due to time variability of the UWA channel. Commonly, in a horizontal medium-range UWA channel, typical multipath spreads are about 10ms.

## 2.3 Doppler

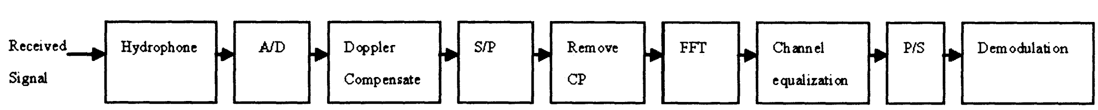
There are two aspects to cause the Doppler. The first one is the motion of sea surfaces and currents. Thus, the UWA channel is a double spread channel. The second one is the relative motion between transmitter and receiver. Normally, Doppler shift is much lager than Doppler spread and has to be compensated in the receiver, especially for OFDM system, which is very sensitive to frequency offset.

## 3. OFDM system for medium-range underwater acoustic communication

### 3.1 system confiugration




(a) Transmitter




(b) Receiver

Fig.1. Block diagrams of UWA OFDM system

Fig.1 shows simplified block diagrams of UWA OFDM system.

In the transmitter, the input data is a serial bit-stream that is to be mapped. After that, the data streams are converted from serial to N-paralled data streams and then a pilot signal is inserted. The modulation of OFDM is conducted by using IFFT. The cyclic prefix signal is used to reduce the effect of ISI and ensure the orthogonality of sub carriers. It is followed by P/S and D/A conversion.

In the receiver, according to [5], Doppler shift, especially the Doppler shift index $\Delta$ is estimated by using cyclic prefix and is compensated effectively by resampling (using a sampling rate $(1+\Delta)/T$ in the receiver different from the rate 1/T in the transmitter) the received signal. It is followed by S/P and FFT. The channel is estimated by using the pilot signal, and the phase variety must be tracked in OFDM system. Equalization is then implemented in time domain.

### 3.2 System parameters

For any UWA communication system, the most important parameter is to choose a carrier frequency, which is mainly dependent on range and ambient noise. Based on sonar equation, the optimal frequency can be determined by

$$f_0 = \left( \frac{70.7}{r} \cdot \frac{d(FM)}{df} \right)^{1/2} \quad (2)$$

in which, $FM$ is defined as:

$$FM = SL - (NL - DI + DT) \quad (3)$$

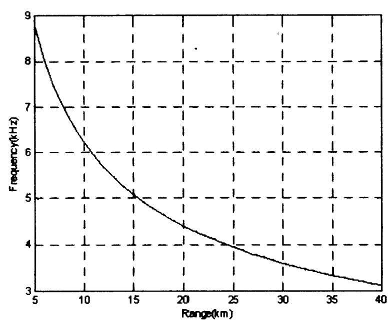



Fig. 2. Relation between range and frequency

For 10 km UWA communication, the optimal carrier frequency is about 6 kHz.

The trade-off among other parameters of OFDM system is made based on bandwidth, data rate and so on. Usually, guard interval should be 2~4 times the root mean square maximum time delay. Table1 shows the parameters of this system.

TABLE 1 OFDM UWA parameters

| Guard interval | FFT/IFFT | Symbol duration |
|---|---|---|
| 0.05s | 0.2s | 0.25s |
| Bandwidth | Bandwidth efficiency | Number of sub carrier |
| 3kHz | 1.6 | 600 |

## 4. Simulations and Experiments

The parameters of OFDM system used for performance simulation are showed in Table 1. A linear frequency modulation signal is used for synchronization. The UWA channel is based on the ray model, including eight propagation paths and the maximum time delay is below 50 ms.

M_ary digital modulation can increase the data rate, meanwhile, the distribution of points in the constellation will affect the system performance. Fig.3 shows the comparison of different OFDM systems using BPSK, 4QAM and 8QAM modulation. From Fig.3 it can be seen that this system is suitable for UWA communication due to the low BERs.

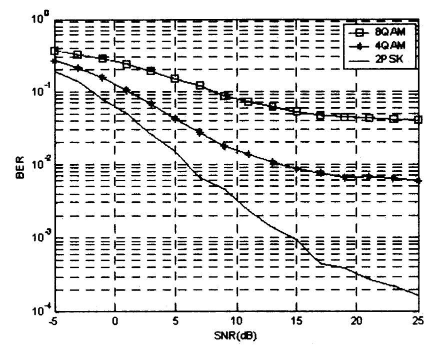



Fig.3. BER Performance of three kinds of modulation

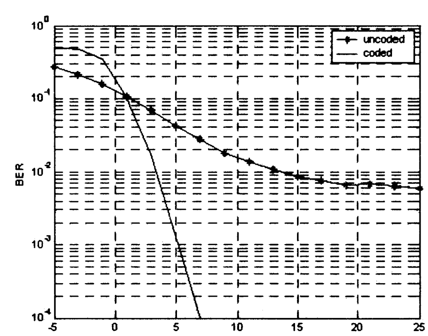



Fig.4. Improvement of performance after Turbo coding

Compared to 2PSK and 4QAM, using 8QAM, the data rate rises at the price of increasing of BER. By using error control coding, the system performance can be improved.

Fig.4 shows the improvement of system performance by using 1/2 rate turbo error control coding. The effect of Doppler shift is shown in Fig.5. The Doppler shift index is assumed to be 0.001. For multi-carrier system, the shift of carrier frequency will lead to inter channel interference (ICI), and will be more serious for OFDM system. It is a disadvantage that OFDM system is very sensitive to frequency shift. If there is no compensation for frequency shift, correct decoding will not be more efficient. Also, Fig.5 shows the system performance after Doppler compensation. The effect of Doppler can be removed by this method.

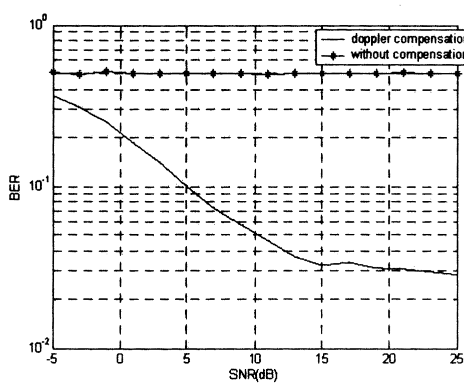



Fig.5. Effect of Doppler shift

In order to evaluate the performance of the OFDM system, an experiment of UWA communication in a lake was conducted. The experimental results demonstrate that at the distance of 5km and 10km, the data rate can reach 9kps and 2.8kps respectively with BER less than $10^{-4}$.

## 5. Conclusion

OFDM has been succeeded in the application in DAB and xDSL. Recently, it has been used in UWA communication. In this paper, an OFDM system for a 10km range UWA communication is designed and implemented. The performance of this system is analyzed. Based on the results of experiments in lake, it is shown that this OFDM system is more efficient for high rate UWA communication not only at short range, but also at medium range.

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