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Frequency Diversity for OFDM Mobile Communication via Underwater Acoustic Channels

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Abstract: The major constraint on the performance of orthogonal frequency division multiplexing (OFDM) based underwater acoustic (UWA) communication is to keep subcarriers orthogonal. In this paper, Doppler estimation and the respective compensation technique along with various diversity techniques were deliberated for OFDM-based systems best suited for underwater wireless information exchange. In practice, for mobile communication, adjustment and tuning of transducers in order to get spatial diversity is extremely difficult. Considering the relatively low coherence bandwidth in UWA, the frequency diversity design with the Doppler compensation function was elaborated here. The outfield experiments of mobile underwater acoustic communication (UWAC) based on OFDM were carried out with 0.17 bit/(s·Hz) spectral efficiency. The validity and the dependability of the scheme were also analyzed.

Keywords: underwater acoustic channel; orthogonal frequency division multiplexing (OFDM); underwater acoustic communication; frequency diversity; Doppler estimation; Doppler compensation
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1 Introduction

Compared with traditional single carrier (SC) coherent underwater acoustic communication (UWAC), OFDM has many advantages such as robust anti-multipaths and anti-impulse noise capability, higher speed transmission capacity, and simpler implementation (Lin Yun *et al*., 2010). Thus, it has become one of the hottest spots in high demand for high speed UWAC research in recent years. However, the application of OFDM in mobile UWAC is strictly restricted due to its Doppler frequency sensitivity behavior. Nowadays, the research analysis specifically for Doppler compensation via underwater acoustic (UWA) is attracting more attention from both domestic and international researchers (Huang *et al*., 2009; Li *et al*., 2007). Many analyses and studies regarding the differences of Doppler shifts per path have been carried out in detail (Li *et al*., 2008; Li *et al*., 2007; Kang *et al*., 2007). The basis of all these methods is derived from Sharif's time domain re-sampling (TDR) (Sharif *et al*., 2000), i.e. the method taking advantage of similarity between the transformed waveform and the original one. The method of TDR relies on the concept that the receiving signal is the compressed (or expanded) copy of the transmitted signal with a fixed Doppler shift ratio such that the original signal can be reconstructed by decompressing (or de-expanding) the received signal. Restructuring of the original signal seems to be simpler but requires huge calculation in terms of cost and performs poorly in anti-acceleration scenarios (Xu, 2009). Therefore, it is difficult to meet the requirement of real-time communication systems. In order to overcome the drawbacks of the traditional Doppler shift compensation technique, a new method called frequency domain re-sampling (FDR) is introduced in this paper, and the Fast FDR (FFDR) method is also provided to carry out the Doppler shift compensation more efficiently.

According to the simulation results and outfield experiments, it is found that the sole use of the FFDR scheme or TDR scheme cannot meet the reliability conditions of the UWAC system. The channel structure and the Doppler shift is usually not uniform due to random motion of subcarriers because of the extremely complex behavior of the UWA channel. Therefore, the original bit error rate (BER) may remain high even after the compensation of the Doppler shift. To mitigate this problem, a spatial diversity technique that can provide more than one copy for joint decisions is widely adopted in UWAC. Unfortunately, the demand of sonar array size restricts the application of the spatial diversity technique, so the device carriers usually need to construct a long line sonar array for obtaining effective diversity gain. In this paper, a frequency diversity technique other than spatial diversity is adopted (Zhao, 2010). Considering the UWA channel's property, i.e. the small frequency correlation radius, several copies can be obtained by sending the same information on the certain sub-channels which can be calculated to make sure that each copy's fading is irrelevant. A communication scheme based on FFDR and a frequency diversity technique is proposed in this article for a mobile UWAC. It is verified that the signal Doppler shift can be timely tracked and efficiently compensated. Moreover, the frequency diversity gain is

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also effectively achieved from the results of the Monte Carlo simulation, the experiments in the underwater acoustic channel simulation lab and also in Songhua Lake.

The rest of this paper is organized as follows. Section 2 analyzes the Doppler effect on OFDM symbols. Section 3 presents the details of the FFDR compensation method, the frequency diversity technique, and the proposed design for joint Doppler compensation with their simulation results. In section 4, experimental results are reported with data collected in POOL08, POOL09, and LAKE09 experiments. The conclusion is in section 5.

2 Analyses of the Doppler effect on OFDM

The behavior of the Doppler effect for UWA communication is extremely complex and different compared to RF communication due to the low transmitting speed of sound in water. The Doppler effect on OFDM symbols can be modeled as a wideband process because the respective frequencies have their particular Doppler shifts even when they can share a Doppler compression factor λ (Wang, 2010). In the case of OFDM, let f_k denote the kth sub-carrier frequency, f_0 the carrier frequency, and Δf the successive subcarriers spacing. Considering the case of relative motion between the devices carriers of the communication system, the received practical frequency $f_k^{'}$ of the kth subcarrier can be expressed as:

$$f_k^{'} = \lambda f_k = \lambda(f_0 + k\Delta f) \tag{1}$$

where $\lambda = (v\cos(\theta) + C)/C$ denotes the Doppler compression factor, v the relative velocity, C the velocity of sound in water and θ is the incidence angle. If, $f_0 = k^{'}\Delta f$, the received frequency of the kth subcarrier $f_k^{'}$ can be simply written as:

$$f_k^{'} = \lambda(f_0 + k\Delta f) = \lambda(\kappa\Delta f) \tag{2}$$

Such that $\kappa = k + k^{'}$.

In the time domain the OFDM signal can be expressed as:

$$s(t) = \mathrm{Re}\{\sum_k s_k \exp(\mathrm{j}2\pi f_k t)\} \qquad 0 \le t \le T \tag{3}$$

s_k is the information carried by the kth subcarrier of the complex signal. The formula $f_k = f_0 + k\Delta f$ denotes the frequency of the kth subcarrier.

Considering the case of relative motion between the transmitter and the receiver, the received signal, transmitted through M multipaths can be expressed as:

$$\begin{aligned} y(t) = \mathrm{Re}\left\{\sum_{n=1}^{M} c_n \left[\sum_{k=0}^{N-1} s_k \exp\left(\mathrm{j}2\pi\left(f_k + f_{k,n}\right)\left(t - \tau_n\right)\right)\right]\right\} = \\ \mathrm{Re}\left\{\sum_k \eta_k(t) s_k \exp\left(\mathrm{j}2\pi f_k t\right)\right\} \end{aligned} \tag{4}$$

$$\eta_k(t) = \sum_{n=1}^{M} c_n \exp\left(\mathrm{j}2\pi\left(f_{k,n}t - \left(f_0 + f_{k,n} + k\Delta f\right)\tau_n\right)\right) \tag{5}$$

where, c_n is the gain of the nth multipath, τ_n denotes the nth multipath time delay, and $f_{k,n}$ the frequency of the kth subcarrier arriving by the nth route with Doppler shift. So $f_{k,n}$ can be expressed as

$$f_{k,n} = (f_0 + k\Delta f + f_i(t))\frac{v}{c}\cos\theta_n \tag{6}$$

Now, θ_n is the incidence angle arriving at the receiver through the nth path. It is assumed that the angles of different paths arriving at the receiver vary little in long distance communication viz. $\theta_n = \theta_0$ is constant. The frequency interference caused by acceleration motion and other interferences is denoted as $f_i(t)$. To simplify Eq.(6) it is supposed that $f_i(t) = 0$.

Then

$$\begin{aligned} f_{k,n} = (f_0 + k\Delta f + f_i(t))\frac{v}{c}\cos\theta_0 = (f_0 + k\Delta f)\frac{v}{c}\cos\theta_0 = \\ (\lambda - 1)(f_0 + k\Delta f) \end{aligned} \tag{7}$$

If Eq.(2) is satisfied, the Doppler shift can be considered as a geometric proportion process by the definition of the constant relative velocity. So in theory, the Doppler shift can be efficiently compensated by FDR technology.

3 The designs for mobile commutation

3.1 The Doppler compensation method based on FFDR

One of the core Doppler compensation problems is the Doppler real time tracking. It is found that due to the fast time-varying UWA channel and the non-uniform motion of devices carriers, the ability of the traditional method cannot satisfy the demand of precise Doppler measurement, i.e. a double LFM scheme to measure the interval change and a time separate continuous wave (CW) scheme to test the frequency altering. To rectify this problem, a method of FDR with CW tracking (valid for varieties of Doppler) is proposed in this section. The tracking signal is designed to be orthogonal with the subcarriers of the OFDM and is separated from the OFDM signal in the frequency domain.

A tracking signal is added to the original OFDM signal in the time domain. The frame structure of the signal is shown in Fig.1:

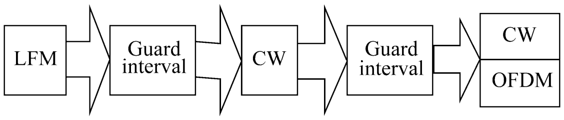


Fig.1 The sketch map of the frame structure

Focusing on the signal variations influenced by Doppler shift, the received signal can be expressed as:

$$s'(t)=\mathrm{Re}\left\{\sum_{k} s_k \exp\left(\mathrm{j}2\pi\lambda f'_k t\right)\right\} \qquad 0\le t\le T \tag{8}$$

By Eq.(8) all the subcarriers are orthogonal to each other. The information carried by each subcarrier can be extracted perfectly through each subcarrier. Namely, using a discrete Fourier test (DFT) algorithm, the modified OFDM symbol can be demodulated properly without re-sampling it in the time domain. In this paper, this method is named 'FDR'.

Unfortunately, FDR needs a large amount of calculation and huge memory storage, so the fast DFT (FFT) algorithm is chosen as an approximate substitution scheme to DFT. Through the experiences gained from the Monte Carlo simulations and the outfield experiments, it is concluded that if the frequency domain resolution is high enough (i.e. capable to give Doppler residua of each subcarrier 4%–5% lower than that of Δf), it will not reduce the performances of the commutation system dramatically. Furthermore, the excess demand on the hard devices can also be cut down. The main points of the Fast FDR (FFDR) method are listed below:

1) Choose a certain length of FFT (much longer than the OFDM symbol length) to each Doppler affected OFDM symbol for getting frequency spectrum sample with high resolution.
2) Find the Doppler compression factor of each symbol by measuring the tracking CW.
3) Calculate the real position of the respective subcarrier in the frequency domain based on the Doppler compression factor.
4) Pick out the nearest spectrum sample according to the calculation result from step 3), and obtain the data.

If the frequency spectrum resolution in step 1 is high enough, the error caused by rudimental can be neglected by considering the other interferences.

Fig.2 shows the BER curve of different frequency spectrum resolution. It is assumed that the Doppler compression factor λ is constant within a symbol while different symbols are affected by a nonconforming λ (the change of two successive symbol's factor λ is less than 1.5% of its own). The parameters of the system are as follows: the bandwidth ranges from 6 kHz to 12 kHz; the sampling rate is 48 kHz; the duration of each symbol is 171 ms; Δf is 5.86 Hz; the circulation prefix (CP) is 43 ms and the circulation suffix (CS) is 6 ms; the comb pilot frequency interval is 3 and QPSK mapping is applied.

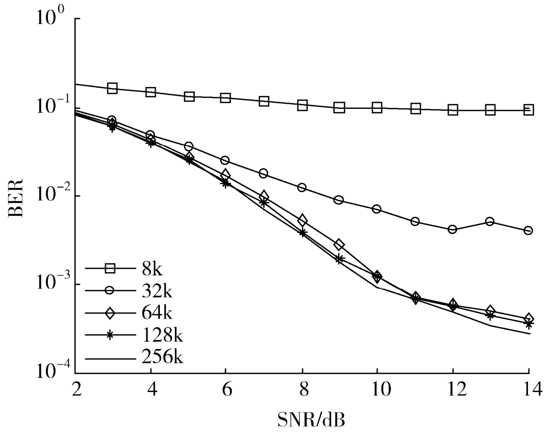


Fig.2 The precision analysis of frequency selection

Fig.2 explains that the BER does not decline drastically with using more than 64k FFT length. Therefore, it can be assumed that the demand of the underwater acoustic communication system can be met by using the 64k FFT demodulation method with a proper design.

3.2 Frequency diversity technique

It is found that the original error rate is still sometimes high even with the Doppler compensation procedure. Therefore, the spatial diversity technique that has effective diversity gain is studied widely in the high speed UWAC. But as the analysis mentioned in section 1, the spatial diversity is hard to be realized in mobile UWAC cases. It is noticed that the coherence bandwidth is usually quite small in a shallow sea channel. The coherent radius is usually between 100 Hz and 300 Hz while the bandwidth of the negative gradient layer channel is much less than 100 Hz. Namely, the diversity gain can be achieved simply by frequency band division. So the frequency diversity instead of spatial diversity technique is adopted in this paper.

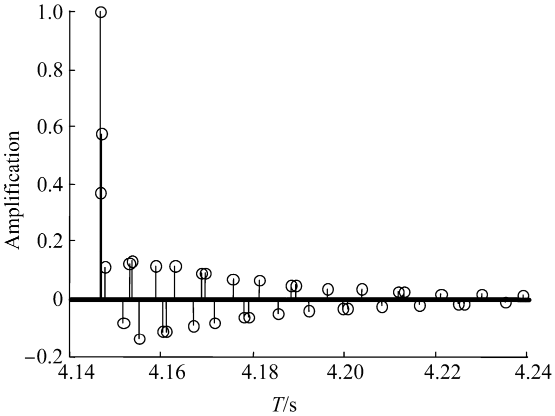


Fig.3 The impulse response of the simulation channel

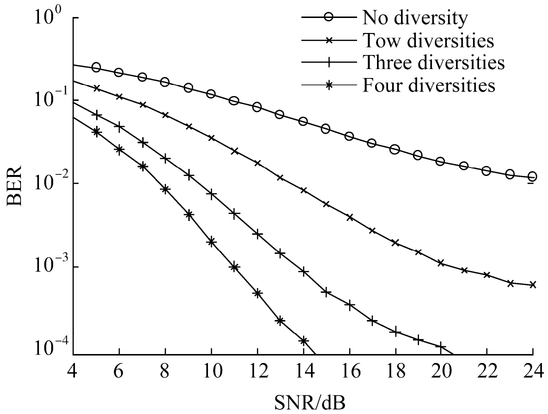


Fig.4 The BER of QPSK with MRC

To validate the feasibility of the frequency diversity, Monte Carlo simulation experiments were carried out. The impulse response of the simulation channel is shown in Fig.3. The signal transmitter is laid 15 m under the water, and the hydrophone is placed at 20 m depth with a horizontal distance 6 200 m from the transmitter. There is no relative movement between two hydrophones, and the other parameters are the same as the simulation in section 3.1 except that CS is 22 ms. Fig.4 is the BER curve of different diversities with maximal ratio combining (MRC) (Duman and Ghrayeb, 2008).

Considering the case of mobile communication, let $s_{j,i}$ denote the information carried by the *l*th subcarrier in the j^{th} branch of the total band subset. It is assumed that $\beta_{j,i}$ denotes the interference coefficient from all the other subcarriers such that the information after the FFDR compensation $s'_{j,l}$ can be written as:

$$s'_{j,l} = \sum_{i=1}^{N'} s_{j,i} = \beta_{j,l}s_{j,l} + \sum_{\substack{i=1\\ i\neq l}}^{N'} \beta_{j,i}s_{j,i} = \beta_{j,l}s_{j,l} + w \tag{9}$$

N' represents the number of the total subcarriers in one subset. The signal transmits over different channels and the fading of different subcarriers is independent, so the interference factor w can be regarded as an independent interference. Therefore the inter-symbol interference (ISI) can be mitigated by the frequency diversity technique.

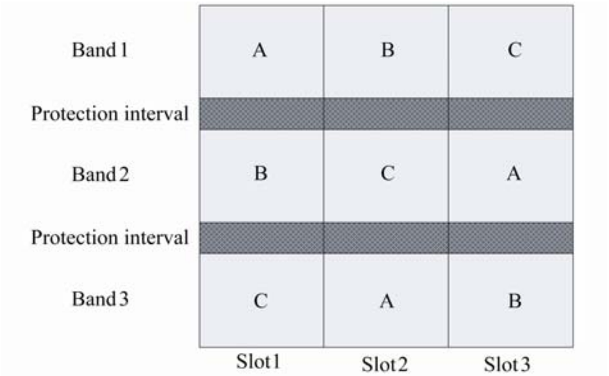
3.3 A design for Doppler compensation

The FFDR compensation with the multi-band time and frequency interlacing OFDM method originates from the MB-OFDM-UWB technique in wireless communication (Chen, 2008). The significance of the multi-band division is that the communication system can achieve the diversity gain with a high original error rate.

In the case of mobile communication, the MB-OFDM scheme in UWAC can obtain the time diversity gain, the frequency diversity gain at the same time. Further, the multi-user communication can also be effectively realized by dividing up the frequency band easily.

The MB-OFDM scheme in UWAC designed in this paper is as follows:
1) Divide the available band into P sub-bands. A certain reasonable protection space should be left between each sub-band according to the coherent bandwidth of the UWA channel.
2) Generate P OFDM sub-symbols at a time and interlace the information in the respective sub-symbol following a certain table. Then the P new OFDM sub-symbols are obtained.
3) Transform the new OFDM sub-symbols to the symbols in the time domain by IFFT, and then the P OFDM sub-symbols in a time domain are obtained on the base band.
4) Modulate the P time domain OFDM sub-symbols to their own transmitting band and superpose them into a whole OFDM symbol in time domain.
5) Modulate the P sub-symbols again following the method shown by Fig.5.

Repeat the above process Q times. Generally $1 \le Q \le P$. Then the Q full time domain signal can be generated.



	Slot1	Slot2	Slot3
Band 1	A	B	C
Protection interval	▨	▨	▨
Band 2	B	C	A
Protection interval	▨	▨	▨
Band 3	C	A	B

Fig.5 The schematic diagram of the system

The demodulation process is the reverse of the modulation process, so it can be simply seen as P OFDM sub-symbols obtaining the Q diversity gain by dual interleaving in both the time domain and frequency domain.

To validate the feasibility of the commutation system, Monte Carlo simulation experiments are carried out under the channel condition shown in Fig.3.

The simulation adopts identical parameters in section 3.2 besides considering the nonconforming relative motion. Doppler compression factor λ is constant within a symbol while different symbols are affected by a nonconforming λ, and the difference of two successive symbols is less than 2.5% of their own. Subsequently, QPSK and 8PSK mapping are applied.

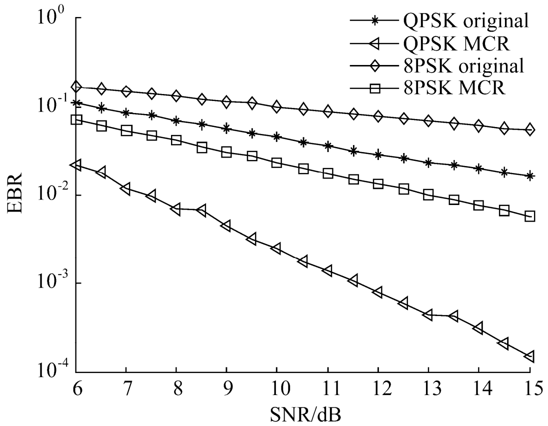


Fig.6 The BER of QPSK&8PSK with MRC

The system performance in mobile communication is shown in Fig.6. From the simulation results it can be found that the system track and compensates the variations of the Doppler shift successfully. The diversity gain is also properly achieved. Consequently, it is believed that reliable communication can be realized with a high efficiency code in a mobile UWAC.

4 Experimental results

4.1 Experimental results of POOL08 and POOL09

In order to validate the feasibility of the Doppler compensation algorithm and the performance of the MB-OFDM system, several experiments were done in the simulation channel lab of Harbin Engineering University.

4.1.1 Experimental results on FFDR

The mobile communication pool experiment was carried out in August 2009. The depth of the water was 1.5 m. The transmitter transducers and the receiving hydrophones were placed about 0.8 m below the surface. The transmitting transducer was shuttled from 4 m to 8 m towards the receiving hydrophone due to the limited length of the pool.

In this experiment, the communication bandwidth is chosen as 3.5–7.2 kHz. The total number of the subcarriers is 601. The symbol duration is 171 ms and Δf is 5.86 Hz. The CP is 43ms and the CS is 6ms. The comb pilot frequency interval is 3, QPSK mapping. The compensation results of each symbol are listed in Table 1.

Table 1 FFDR compensation results

Symbol	$V/(\mathrm{m \cdot s^{-1}})$	FFDR (64kFFT)	Original error rate
1	1.024	0.070	0.325
2	0.983	0.043	0.350
3	0.945	0.019	0.386
4	1.067	0.067	0.358
5	0.877	0.018	0.376
6	0.603	0.026	0.342

(a) Before FFDR (b) After FFBR

Fig.7 The effect of FFDR compensation method

The system tracked and compensated the Doppler changing successfully as mentioned in the results of Table 1 and Fig.7. The symbol 1 and 4 performances are much poorer than the other symbols because the acceleration inside a symbol is much greater compared to other symbols, which is also the limitation of this method.

4.1.2 Experimental results on MB-OFDM

In September 2008, a pool experiment of MB-OFDM was carried out in the simulation channel lab of Harbin Engineering University.

The transmitting transducer and the hydrophone are both 0.8m below the water surface with a 10 m distance. The system parameters are the same as the simulation mentioned in section 3.2.

The impulse response of the pool channel tested by an LFM signal is shown in Fig.8.

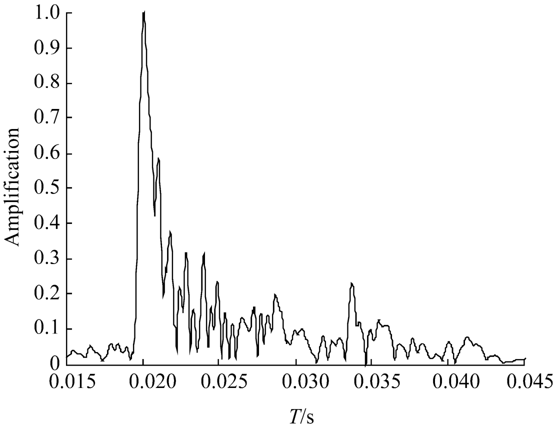


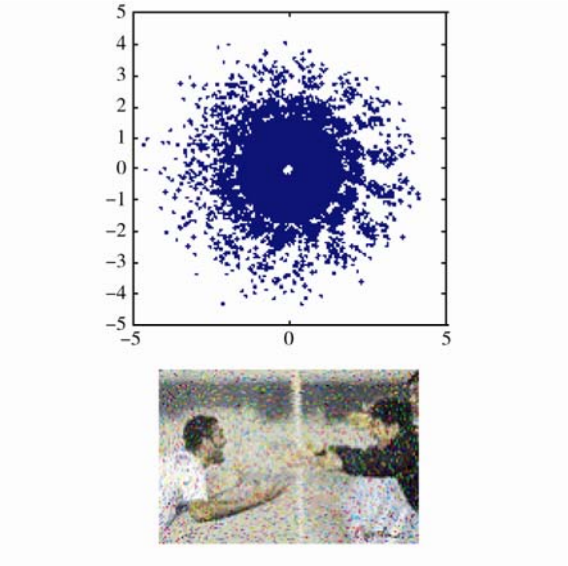
Fig.8 The schematic diagram of the channel in time domain

The MRC technique with 16PSK mapping is applied in the experiment. The results are shown in Fig.9. Comparing Fig.7(a) with Fig.7(b), we can see clearly that the system obtained diversity gain.

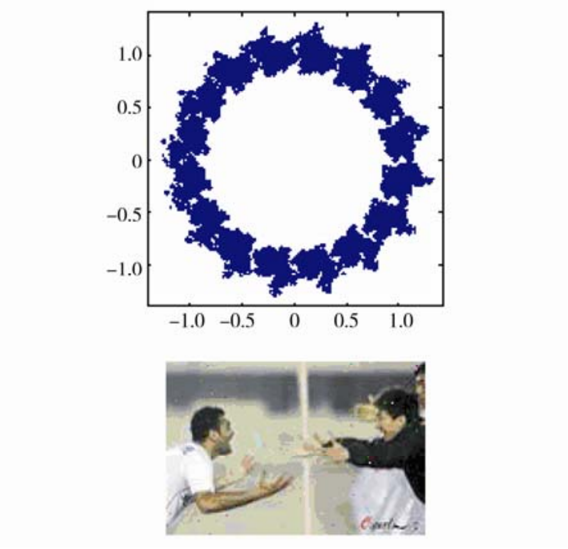
4.2 Experimental results of Songhua Lake09

In September and October 2009, an outfield mobile UWAC experiment of MB-OFDM FFDR was held on Songhua Lake in Jilin City.

The receiving boat “Flying Dragon One” was attached to Jingui Island. The coordinates of the boat were ($43^\circ 42'24''$ N, $126^\circ 42'49''$ E). The transmitting boat “Independence” was about 3.3 km away from the receiving boat to the northeast. The main parameters of the experiment system are listed in Table 2.



(a) Original error rate 0.0624



(b) MRC error rate 0.0012

Fig.9 The effects of frequency diversity method

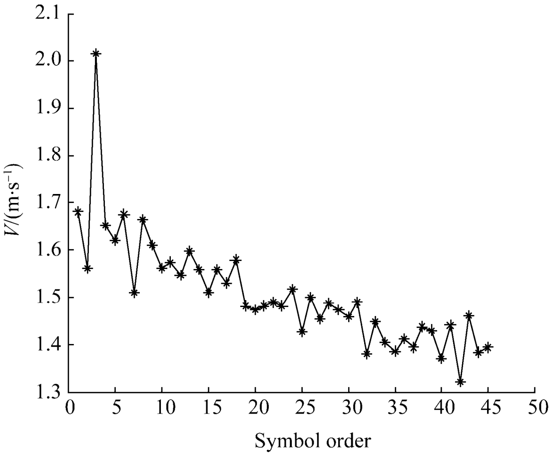


Fig.10 Relative speed estimated by FFT test

Table 2 Parameters of OFDM system

Items	Value	Items	Value
FFT Length	8192	Code Rate	1/2
Sampling Rate/kHz	192	P	2
Effective Subcarriers	300	Mapping	QPSK
Δf /Hz	5.86	T /ms	171
Band Range/kHz	3.5–7.2	T_g (CP)/ms	43
CW/kHz	3.5	T_b (CS)/ms	22
B /kHz	3.7	T' /ms	235
N	601	Bits Rate/(kbit·s^{-1})	5.04
Pilot	Comb, LS linear interpolation	Effective Bits Rate/kbit/s	0.63

The relative radial velocity between the two boats tracked by CW is shown in Fig.10. It can be clearly seen that the transmitter is moving to the receiver at a speed of 1.5 m/s with a negative acceleration.

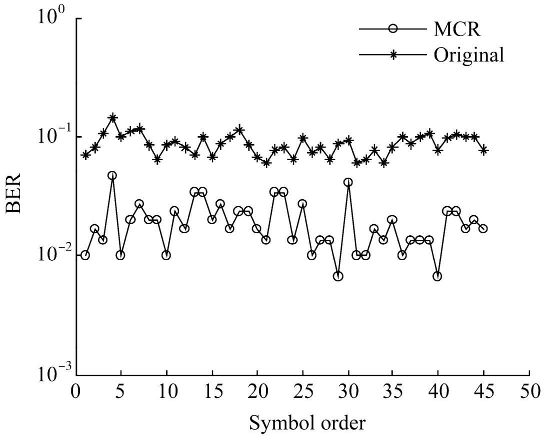
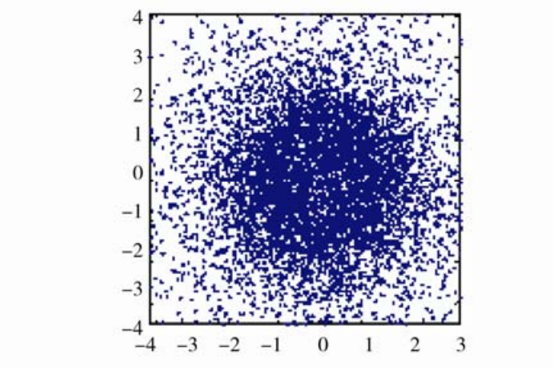


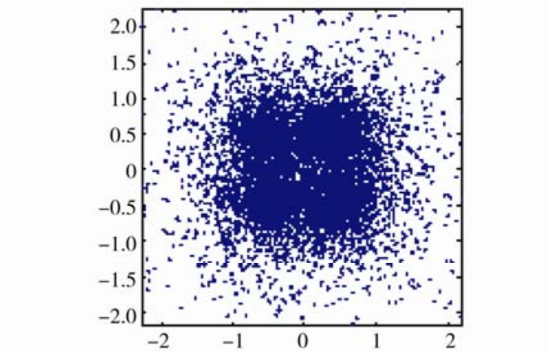
Fig.11 Bit error rate for diversity combination and original

Fig.11 shows the effect of frequency diversity. Each symbol's EBR is lower after MRC processing.

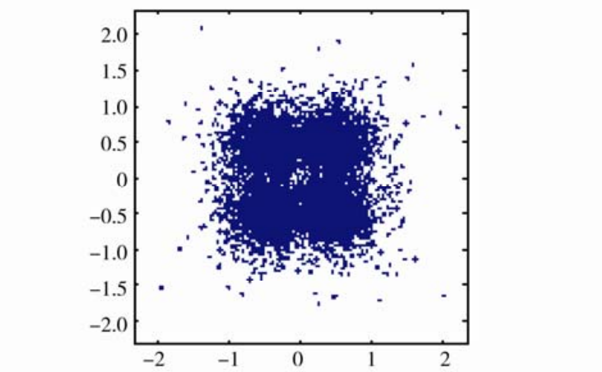
Fig.12 explains three constellation maps on different process steps and a reconstructed picture. Fig.12(a) is the received signal's original constellation map; it is impossible to obtain any useful information through this map.



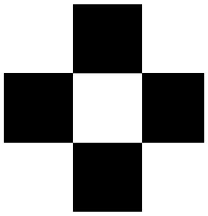
(a) Original



(b) After FFDR



(c) After MRC



(d) Reconstructed information

Fig.12 The effect of different steps

Fig.12(b) is the map after the FFDR processing. From this map, it can clearly be seen that QPSK mapping is adopted in this communication system, but the information errors still remain high. Fig.12(c) is the map after the MRC processing. Frequency diversity gain is achieved so that the information can be extracted from Fig.12(c) much more reliably than from Fig.12(b). Finally, in Fig.12(d), the recovered picture with the Convolution Code (CC) gain is shown.

The original error rate is about 50% because of the relative motion. After the FFDR signal processing, the EBR is down to around 10%, but still is high because of the deviation of the Doppler measurement, bad channel condition, and rapid change of the ship speed. Finally by using MRC, EBR decreases 4.5% more. All the symbols achieved obvious diversity gain. Also, after the CC decoding process, the achieved EBR is below 10^{-5}.

5 Conclusion

The feasibility of FFDR and the frequency diversity technique in the UWAC was analyzed and verified by the simulation and field experiment. The multi-band OFDM time frequency interweave mobile communication scheme was proposed and demonstrated through simulation. Moreover, outfield experiments were also carried out with a distance of 3.3 km between the transmitting ship & receiving ship and a relative velocity of 1.5 m/s with negative acceleration. Reliable mobile communication was successfully accomplished between the two hulls with a spectral efficiency of 0.17 bits/(s·Hz).

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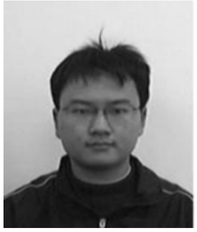
Gang Qiao was born in 1974. He is a professor of Harbin Engineering University. He presided over 10 research studies, including the National High Technology Research and Development Program of China.



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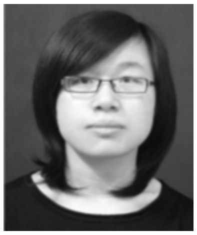

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