

# Underwater Acoustic Communication Based on Hyperbolic Frequency Modulated M-ary Binary Orthogonal Keying

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## Abstract

*In this paper we propose the HFM-MBOK (Hyperbolic Frequency Modulated-M-ary Binary Orthogonal Keying) modulation technology based on frequency bands allocation which is suitable for underwater acoustic communication. This solution has characteristic of constant envelope. Under the guidance of the theory, we test the practicability of the system through MATLAB simulation. This system uses MFSK-MBOK cascaded technology and reduced calculation amount significantly. Finally, the underwater acoustic communication system we proposed has been tested by pool experiments. The experimental results show that the system is able to achieve a robust and reliable communication under the conditions of low signal-to-noise ratio and strong multipath.*

**Keywords:** *underwater acoustic communication, HFM spread spectrum, Doppler Effect*

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## 1. Introduction

Shallow water acoustic channel is a quite complex space-time-frequency varying channel, the inherent characteristics, such as extensive multipath, narrow bandwidth, low frequency and high ambient noise [1]. Acoustic signals propagate underwater at a speed of 1500m/s, it is much slower than the speed of electromagnetic wave, minor fluctuations of the sea waves and relative movement of receiver-transmitter will cause much larger Doppler frequency shift than common wireless communication. Besides, multiple reflection, refraction of sea surface, seabed and step gradient structure of acoustic velocity in ocean will cause extensive multipath in underwater acoustic channel and produce strong amplitude and phase fluctuation [2]. Therefore, how to achieve a robust and reliable communication in complex and changeable underwater acoustic channel is a key problem in underwater acoustic communication area which is necessary to deal with.

People take a variety of methods to improve the quality of underwater communication, and spread spectrum technology is applied to underwater acoustic communication, because it has strong anti-interference ability, high concealment, and effective anti-multipath characteristic and can achieve better performance under the condition of low signal-to-noise ratio. Underwater spread spectrum communications technologies include FHSS and DSSS, the former has poor performance under the condition of long distance and low signal-to-noise ratio, it needs extra channel coding technology to improve its performance; the latter is very sensitive to Doppler frequency shift, it needs strict synchronization and complex phase real-time tracking technology [3].

Faced with the shortage of traditional spread spectrum, researchers advise applying Chirp spread spectrum (CSS) technology to underwater communication [4]. CSS is different from FHSS and DSSS, it need not add pseudo-random sequence, but uses frequency linearity characteristic of Chirp signal itself. Compared to traditional spread spectrum signal, Chirp signal has high processing gain and inner anti-interference characteristics; it also makes some progress in anti-Doppler frequency shift. These characteristics make Chirp spread spectrum technology applicable in the area of underwater acoustic communication, and related studies have also begun to enter the application stage. HFM signal that commonly used in active sonar

has also begun to attract attention recent years [5], some studies show that it is more applicable than Chirp signal in solving Doppler frequency shift appeared in underwater acoustic communication. HFM signal not only has better correlation properties than Chirp signal, but also has Doppler invariance [6], it can improve the performance of underwater communication system in greater extent.

Based on the ideas of designing CSS, this paper chooses HFM signal as modulating signal and designs a new spread spectrum technology which has anti-noise, anti-multipath and anti-Doppler frequency shift characteristics. Compared to Chirp signal, HFM signal has better Doppler tolerance.

## 2. HFM Signal and Its Characteristics Analysis

### 2.1. HFM Signal

Hyperbolic Frequency Modulated (HFM) signal is a common sonar signal [7], it has better Doppler tolerance than Chirp signal. Especially in recent years, HFM signal becomes central issue in underwater acoustic communication, location and anti-submarine sonar areas because of its Doppler invariance. Practice has proved that transmitting or receiving HFM signal on moving platform, it has better detection capability than other signals [8].

HFM signal is a non-linear frequency modulation signal that modulated regularly for hyperbolic function, supposed that  $f_1$  is starting frequency,  $f_2$  is ending frequency,  $T$  is the range of time. If the frequency increases ( $f_1 < f_2$ ), we call it up-HFM, conversely, named down-HFM. A HFM signal can be written as:

$$s(t) = \cos\left[2\pi \frac{\ln(kt + 1/f_1)}{k}\right] \quad 0 \leq t \leq T \quad (1)$$

Where HFM-rate  $k$  is:

$$k = \frac{f_1 - f_2}{T * f_1 * f_2} \quad (2)$$

The instantaneous frequency is:

$$f_i(t) = \frac{1}{2\pi} \frac{dj(t)}{dt} = \frac{1}{kt + 1/f_1} \quad (3)$$

Where  $j(t)$  is the phase, the instantaneous frequency also can be defined as:

$$\frac{1}{f_i(t)} = kt + \frac{1}{f_1} = \frac{f_1 - f_2}{T f_1 f_2} t + \frac{1}{f_1} = \frac{f_1}{f_2} - \frac{1}{f_1} \frac{f_2}{T} t + \frac{1}{f_1} \quad (4)$$

The instantaneous frequency changes with time  $t$  in the form of hyperbolic in the range of  $[f_1, f_2]$ .

**Error! Reference source not found.** shows the time-frequency relationship of HFM signal and Chirp signal. **Error! Reference source not found.** shows the time domain waveform and spectrum diagram of HFM signal, and the frequency is from 10 KHz to 20 KHz.

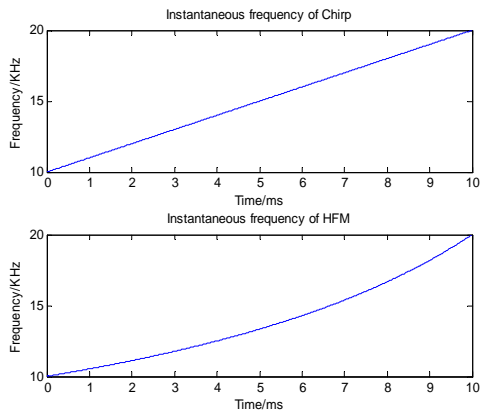


Figure 1. Time-frequency Relationship of HFM Signal and Chirp Signal

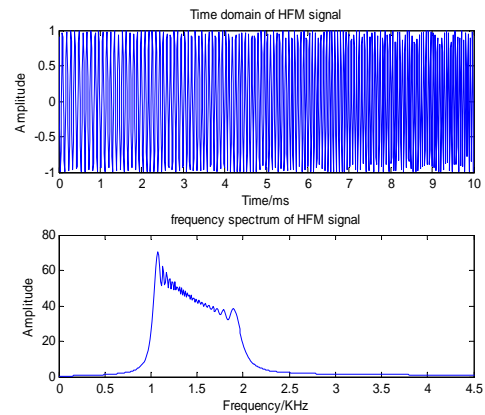


Figure 2. Time Domain and Frequency Domain of HFM Signal

**2.2. Pulse Compression Characteristic**

HFM signal has similar pulse compression characteristic as Chirp signal, as shown in Figure 3. Just as Chirp signal's pulse compression characteristic, the main lobe width of the output of HFM signal in matched filter is  $2 / B$ , the main lobe height is  $\sqrt{BT}$ . HFM signal can replace Chirp signal to build communication system, its pulse compression characteristic is the basic condition. Besides, the HFM signal compared to the chirp signal has the anti-noise, and the anti-multipath characteristics and better Doppler tolerance.

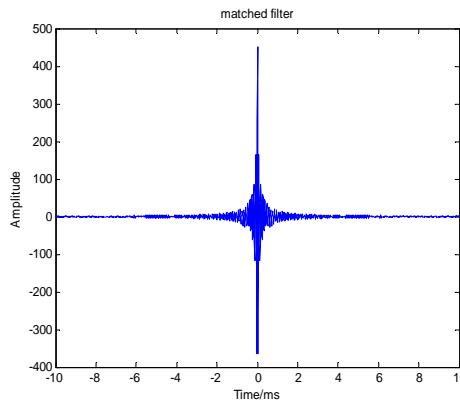


Figure 3. Output Waveform in Matched Filter

**2.3. Doppler Invariance**

We assume that HFM signal occurs Doppler frequency shift during transmission. Similarly, supposing that the relative speed of receiver is  $v$ , acoustic speed is  $c$ , so the Doppler factor can be expressed as:

$$D = 1 + v / c \tag{5}$$

The instantaneous frequency of HFM signal is rewritten as:

$$f_r(t) = \frac{1}{2p} \frac{dj_r(t)}{dt} = \frac{D}{kDt + 1 / f_1} \tag{6}$$

Where the phase is:

$$j_r(t) = 2p \frac{\ln(kDt + 1/f_1)}{k} \quad (7)$$

We set time delay as:

$$Dt = - \frac{D}{f_1' k' D} \quad (8)$$

From (3) we can get:

$$f_r(t - Dt) = f_i(t) \quad (9)$$

The above states that after occurring frequency shift, HFM signal exists a time delay  $Dt$  which makes signals after occurring frequency shift matched with original signals, this is Doppler invariance of HFM signal.

### 3. MFSK-MBOK communications system architecture

The main idea of MFSK-MBOK is combining modulation and demodulation method with multiple BOK demodulation. Receiver used MFSK to select different frequency bands. Compared with MFSK-MCrSK (Multiple frequency shift keying-multiple chirp-rate shift keying), MFSK-MBOK used FFT and matched filter to demodulation. And the limitation of MFSK-MCrSK system is that the structure of demodulation is quite complicated and the computation increases rapidly along with increasing the value of  $M$ .

The following is the example of 4FSK-4BOK modulation and demodulation system, the block diagram of the system is shown as

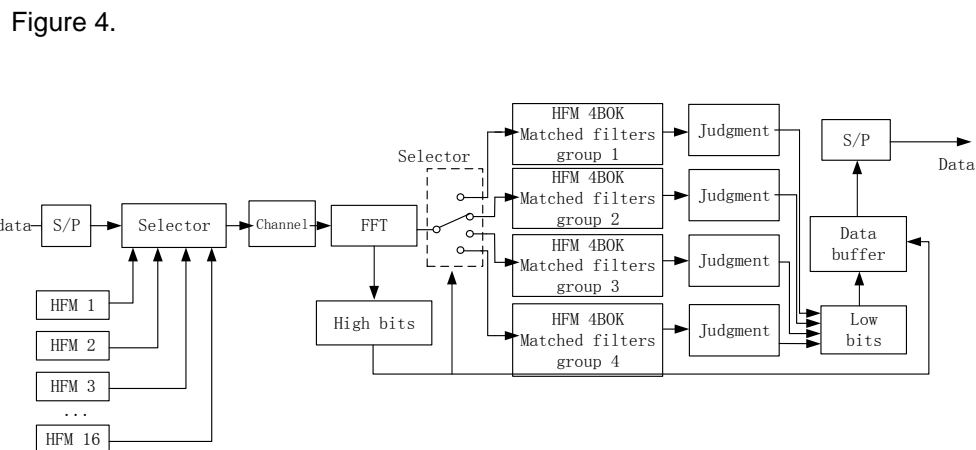


Figure 4. Block Diagram of 4FSK-4BOK Communication System

We supposed that the bandwidth of the communication system range from 10 KHz to 20 KHz, and the bandwidth will be divided into four sub-bands of MFSK (10k-12.5kHz; 12.5k-15k Hz; 15k-17.5k Hz, 17.5k-20k Hz). And each sub-band will be modulated in HFM-4BOK. And the symbol time is 10ms, and each symbol carries 4bits information, so the transmission rate of the system is 400bps. Figure 5 shows that the relationship between symbol mapping and time-frequency diagram of HFM. **Error! Reference source not found.** shows an example of symbol mapping.

Figure 5. Symbol Mapping

Figure 6. An Example of Symbol Mapping

As the scheme we proposed has in common with MFSK, receiver can judge which sub-band the receive data located by using FFT processing similar to MFSK. Based on the location of sub-band, receiver can demodulate the high bits of the symbol. Next, we use matched filters group to processing the receive data in order to get the low bits. Figure 7 shows the FFT domain of four sub-band HFM signals.

High bits of symbol determine which matched filters group is selected. And each matched filters group is equivalent to the demodulation block of single carrier HFM-4BOK that contains four parallel match filters. We can demodulate low bits information by judging the position of correlation peak.

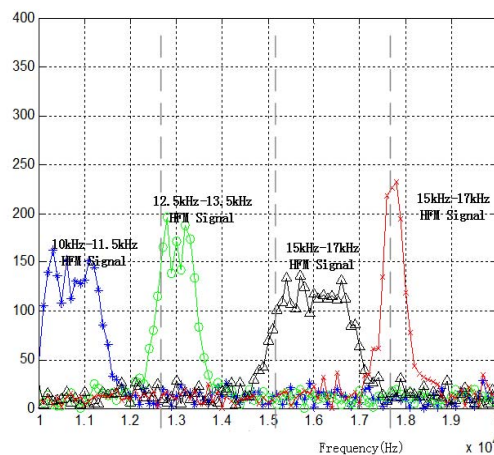


Figure 7. Frequency Domain of each HFM Signal

#### 4. Experimental Verification

Multipath effect is the most severe impact on the communication system in the shallow water acoustic channel, so the environment of non-anechoic pool can simulate the multipath effect in the ocean channel.

The model of the pool is shown as **Error! Reference source not found..** In the figure, point S is the sender Hydrophone, and point R is the receiver. We select the chirp signal to probe channel of the pool, the result is shown as **Error! Reference source not found..** From the figure, we can see that the second path's energy is close to the main path and the delay is quite short. So the experiment can verify anti-multipath feature of the HFM system.

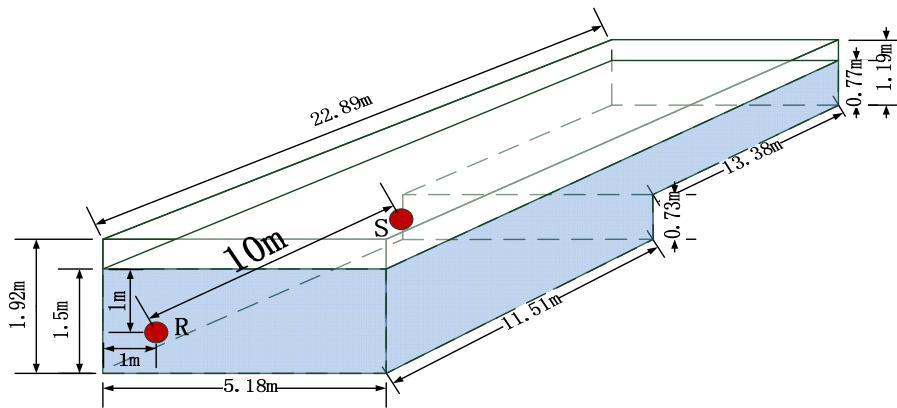


Figure 8. Model of Non-anechoic Pool

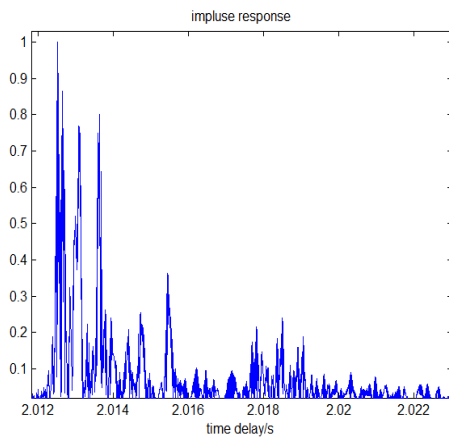


Figure 9. Impulse Response of Pool

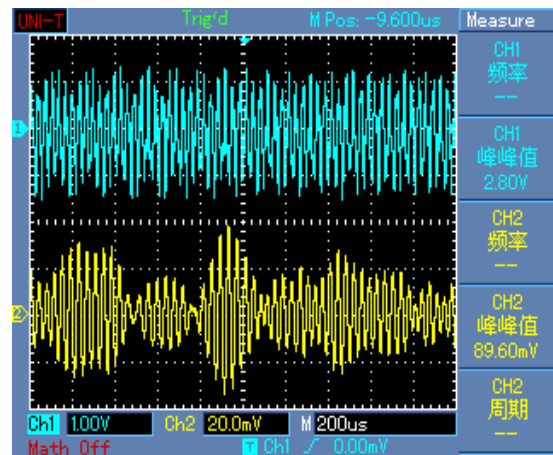


Figure 10. Contrast between Sending Data and Receiving

**Error! Reference source not found.** shows the wave of sender signal and the receiver signal. From the comparison with sender data and receiver data, we can find noise of the pool has little effect on the system. We selected the 64\*64 Lena 8-bit grayscale as the source, and the amount of bits is 32768. Details of the experiment are shown in **Error! Reference source not found.**

Table 1

System	BT	Communication rate	BER		
			-10dB	-15dB	-20dB
4FSK-4BOK	6.25	400bps	$<10^{-4}$	$3.05 \times 10^{-3}$	$6.62 \times 10^{-2}$

The 4FSK-4BOK system can get error-free transmission when the signal-to-noise ratio is 10dB. When the signal-to-noise ratio is -15Db, the BER is less than  $3.05 \times 10^{-3}$



Figure 11. Receiving Image

## 5. Conclusion

In this paper we propose the HFM BOK underwater acoustic communication. The scheme have characteristic of constant envelope. The pool tests results show that the system is able to achieve a robust and reliable communication under the conditions of low signal-to-noise ratio and strong multipath.

In the future, in order to increase the data rate, we plan to combine the phase modulation and the channel estimation. And next, we will do experiments in the ocean environment with moving platform in order to verify the robustness of the scheme we proposed.

## Acknowledgements

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