# *Research on Multi-channel Time Frequency Shift Keying for Underwater Acoustic Communication*

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***Abstract*—Long-range underwater acoustic communication (UWAC) faces many difficulties such as great propagation loss, high ambient noise and long multipath delay. In order to design an excellent long-range UWAC system, it is necessary to increase signal-to-noise ratio (SNR), suppress inter-symbol interface (ISI) and alleviate frequency selective fading. In this paper, a novel time frequency shift keying scheme named as Multi-channel Hex Four Time Four Frequency Shift Keying (McH-4T4FSK) is presented. The scheme is designed by two aspects: high-array modulation at transmitter to improve spectral efficiency and multi-channel processing at receiver to enhance signal-to-noise ratio of received signal. Based on the two aspects mentioned above, there are four time slots and four frequencies in each symbol. Shallow water sea trials are conducted at Taiwan Strait with 30km distance. The results indicate that McH-4T4FSK is a kind of underwater acoustic communication scheme with low BER and good robustness.**

***Keywords-time frequency shift keying, underwater acoustic communication, long-range***

## I. INTRODUCTION

With the rapid development of oceanography, maritime research, offshore oil exploration and maritime defense system in the last three decades, modern cooperative communication network between underwater and land has become an urgent need for efficient information sharing and convenient information communication [1, 2]. Generally, underwater acoustic channels are recognized as one of the most difficult communication media in practice today, and there are many obstacles in developing applicable products although recent research has improved the performance and reliability of the underwater acoustic communication system [3]. Undoubtedly, how to realize remote and robust underwater communication is a pressing problem for overcoming these obstacles.

In order to get robust underwater acoustic communication system, many developing applications, both commercial and military ones, are prone to choose non-coherent modulation as their preferred solutions. Non-coherent detection of multi-frequency shift keying (MFSK) signals has traditionally been considered as the only alternative for channels with rapid phase variation, such as the long and medium range channels in the shallow water [4]. Ref. [5] introduced a kind of communication scheme called as fast frequency-hopped/M-ary frequency shift keying (FFH/MFSK) in order to realize deep-sea remote communication, in which the MFSK signals were modulated twice through the technique of fast frequency hopping so as to suppress frequency selective fading caused by multipath propagation. Ref. [6] proposed a novel frequency group coding (FGC) method different from traditional MFSK frames, in which the neighboring MFSK symbols were mapped to different frequency groups to effectively restrain the severe multipath. Ref. [7] presented an optimal high speed adaptive multi-carrier UWA communication system based on MFSK modulation, and the experiments in a lake confirmed its suitability for high speed multi-carrier UWA communications between 10~30 km medium range in severe acoustic channels. Considering the good performance of time frequency shift keying (TFSK) against multipath interference, Ref. [8] explored the effect of TFSK modulation in UWA communication system, and the results demonstrated its feasibility for UWA transmission over a distance of 5 km at a data transmission rate of 1k bits/s.

This paper presents a novel TFSK modulation named as Multi-channel Hex Four Time Four Frequency Shift Keying (McH-4T4FSK) which includes four time slots and four frequencies. The scheme is characterized by two aspects: high-array modulation at transmitter to improve spectral efficiency and multi-channel processing at receiver to enhance signal-to-noise ratio of received signal. Hence, the UWA communication system not only inherits anti-fading ability from TFSK communication system, but also can effectively extract signal from strong ambient noise due to its multiple narrow band channel.

The rest of this paper is organized as follows. In Section II, the underwater acoustic signal propagation model is introduced. Then, Section III describes the novel TFSK scheme from modulation, frequency mapping and processing at receiver. Section IV presents several sea trial results and analyzes the signals and experiment results. Finally, Section V summarizes this paper.

## II. SIGNAL PROPAGATION MODEL

In general, underwater acoustic signals are influenced by the ambient noise and the multipath propagation effect. The ambient noise affects signal-to-noise ratio directly, while the

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impact of multipath propagation can result in amplitude fading and inter-symbol interference of acoustic signals.

The ambient noise in the ocean can be modeled using four sources: turbulence, shipping, waves, and thermal noise. Among these forces, surface motion caused by wind-driven waves is the major factor contributing to the noise in the frequency region of 100 Hz - 100 kHz, which is the operating region of most acoustic systems. It is noted that most of the ambient noise sources can be described by Gaussian statistics and a continuous power spectral density (p.s.d.) [9].

Multipath formation in the ocean is governed by two aspects: one is sound reflection at the surface, bottom and any other objects, and the other is sound refraction in the water. Since sound refraction is a consequence of the spatial variability of sound speed [10], underwater acoustic propagation signals can actually be viewed as a kind of complex random process. Ref. [11] established a time-varying underwater acoustic channel based on ray theory, and eigen-rays corresponding to direct or reflected multipath can be determined using ray tracing. Considering these discrete multipath, a time-varying channel impulse response can be represented as:

$$h(\tau,\mathrm{t}) = \sum_{i=1}^{N} a_i(\mathrm{t})\delta\left[t-\tau_i(\mathrm{t})\right] \tag{1}$$

where $N$ is the number of multipath, $a_i(\mathrm{t})$ is the amplitude attenuation factor of $\mathrm{i}^{\mathrm{th}}$ path and $\tau_i(\mathrm{t})$ is the $\mathrm{i}^{\mathrm{th}}$ path delay.

Considering the combined effects of additive noise and multipath propagation, the signal denoted by $y(\mathrm{t})$ at received end can be obtained through equation (2):

$$y(\mathrm{t}) = x(\mathrm{t}) * \mathrm{h}(\mathrm{t}) + \mathrm{n}(\mathrm{t}) \tag{2}$$

where $x(\mathrm{t})$ is the transmit signal, and $\mathrm{n}(\mathrm{t})$ is the additive white Gaussian noise.

## III. McH-4T4FSCK SCHEME

Traditionally, diversity techniques are used to achieve diversity effect for the purpose of anti-fading. However, space diversity needs several antennas while frequency diversity may disperse the limited transmitter power. Fortunately, TFSK modulation can overcome those drawbacks to get diversity effect without increasing the number of antenna or dispersing transmitter power. In this section, we will introduce the system design from three aspects of modulation, frequency mapping and processing at receiver.

### *A. Modulation*

TFSK modulation uses signal consisting of orthogonal frequencies to denote information bits during the transmission period [12]. For example, 2-ary TFSK modulation used two frequency signals to denote bit '0' and the other two frequency signals to denote bit '1'. Thus, a binary period is divided into two time slots with the same width. When bit '0' is transmitted, the first time slot is filled with frequency and the second time slot is filled with frequency ; when bit '1' is transmitted, frequency is transmitted firstly and frequency is transmitted secondly.

Similarly, in McH-4T4FSK modulation, four binary bits form a symbol and each symbol period is divided into four time slots averagely. Each time slot is filled with a frequency signal selected from a special frequency group composed by four different frequency signals. The encoding map between symbols and frequency groups can be seen in TABLE I.

TABLE I. ENCODING MAPPING TABLE

| Frequency group | Symbol | Frequency group | Symbol |
|---|---|---|---|
| $f_{11}f_{12}f_{13}f_{14}$ | 0000 | $f_{31}f_{32}f_{33}f_{34}$ | 1000 |
| $f_{12}f_{14}f_{11}f_{13}$ | 0001 | $f_{32}f_{34}f_{31}f_{33}$ | 1001 |
| $f_{13}f_{11}f_{14}f_{12}$ | 0010 | $f_{33}f_{31}f_{34}f_{32}$ | 1010 |
| $f_{14}f_{13}f_{12}f_{11}$ | 0011 | $f_{34}f_{33}f_{32}f_{31}$ | 1011 |
| $f_{21}f_{22}f_{23}f_{24}$ | 0100 | $f_{41}f_{42}f_{43}f_{44}$ | 1100 |
| $f_{22}f_{24}f_{21}f_{23}$ | 0101 | $f_{42}f_{44}f_{41}f_{43}$ | 1101 |
| $f_{23}f_{21}f_{24}f_{22}$ | 0110 | $f_{43}f_{41}f_{44}f_{42}$ | 1110 |
| $f_{24}f_{23}f_{22}f_{21}$ | 0111 | $f_{44}f_{43}f_{42}f_{41}$ | 1111 |

### *B. Frequency Mapping*

In order to improve the SNR of received signal and suppress interference between adjacent slots within a symbol, an available frequency band is divided into four sub-channels represented by J=1, 2, 3, 4 and then four frequencies represented by I=1, 2, 3, 4 are selected from each sub-channel. The four frequencies named as $f_{IJ}$ in each symbol come from different sub-channels. TABLE II shows the frequency mapping $f_{IJ}$.

TABLE II. FREQUENCY MAPPING $F_{IJ}$

| No.in Ch / No. of Ch | I=1 | I=2 | I=3 | I=4 |
|---|---|---|---|---|
| J=1 | $f_{11}$ | $f_{21}$ | $f_{31}$ | $f_{41}$ |
| J=2 | $f_{12}$ | $f_{22}$ | $f_{32}$ | $f_{42}$ |
| J=3 | $f_{13}$ | $f_{23}$ | $f_{33}$ | $f_{43}$ |
| J=4 | $f_{14}$ | $f_{24}$ | $f_{34}$ | $f_{44}$ |

### *C. Processing at Receiver*

At the received end, signals firstly pass through four band-pass filters with different bandwidth so as to improve SNR of sub-channel signal. Then, each sub-channel signal is synchronized respectively followed by symbol demodulation. Further, each received frequency signal in each symbol is correlated by four local carriers to form four peak values for summation in the combiners. The processing diagram of the receiver is shown in Fig.1.

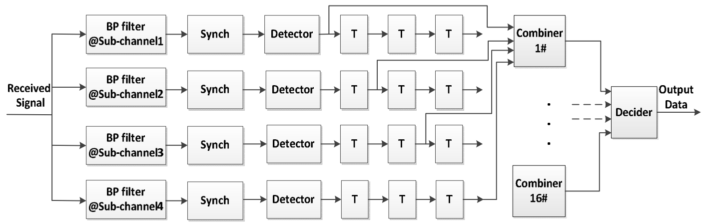



Fig.1 Processing diagram of the receiver

For example, if the received symbol is “0000”, according to TABLE I, the four ordered signals are $f_{11}$, $f_{12}$, $f_{13}$ and $f_{14}$. After demodulation, there is a peak value for each combiner and then the maximum value will be found in combiner 1#.

## IV. EXPERIMENTS

A number of sea trials were carried out at Taiwan Strait in July, 2014. The objective of these experiments was to test the BER performance and robustness of McH-4T4FSK scheme.

### *A. Setup of sea trial*

Fig.2 shows the deployment of sea trial at Taiwan Strait in July, 2014. The distance between sender and receiver is 30 km and the depth is 50 m. A commercial cylindrical transducer deployed at the depth of 30 m was used as acoustic transmitter, while a spherical transducer deployed at the same depth was used as acoustic receiver. The transmitter can provide a source level of more than 190dB when it works at 2 to 6 KHz, while its receive sensitivity is -187dB which is higher than normal hydrophone. The wind speed is from 5 to 11 m/s, which is equivalent to the scale level of 3 to 5.

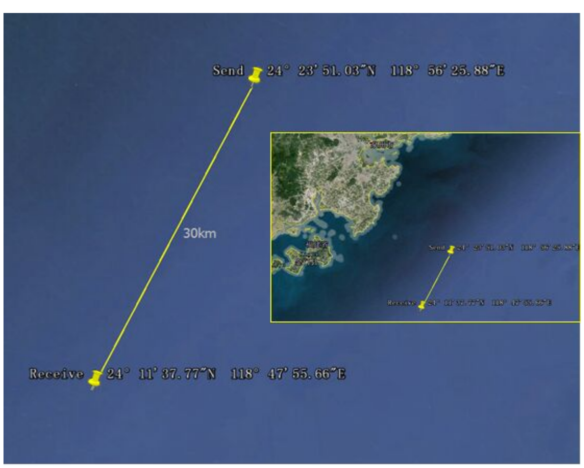



Fig.2 Deployment of sea trial at Taiwan Strait in July, 2014

The frequency band of transmitted signal varied from 2 to 6 KHz with a bit rate of 100 bps. With a fixed transmission source level, the source consecutively broadcasted the signals as shown in Fig.3. The received signals were collected by NI DAQ (NI USB-6259) for off-line processing in the laboratory. Four identical LFM signals with a bandwidth of 1 KHz and a time duration of 2s were used as sub-channel time synchronization. The length of synchronization signal was so long that the signal could be separated accurately. The data signal was equipped with McH-4T4FSK scheme, and each symbol consisted of four frequencies from four different sub-channels. Each frequency signal lasted for 0.01s, and the sub-channels at receiver could get their corresponding signal through their synchronization signals. Otherwise, the tones ahead of the frame were used to test channel conditions.

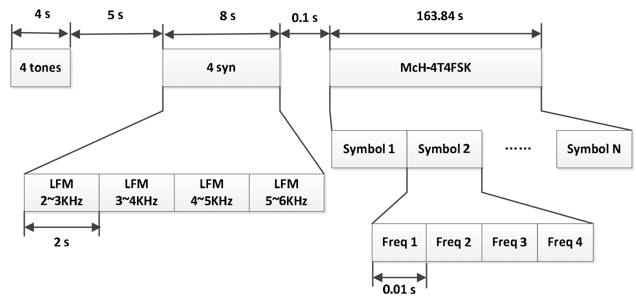



Fig.3 Diagram for transmitted signals

### *B. Analysis of signal and experiment results*

Fig.4 shows channel impulse response (CIR) estimations at Taiwan Strait. The CIR is represented by $h(t,\tau)$ in the figure, where t represents the test time and $\tau$ represents the delay time. There are no obvious direct ways and the ambient noise is high during the sea trial period. What is more, the delay between two paths is more than 50 ms, which is longer than the period of symbol. Obviously, real field experiments can test the robustness of McH-4T4FSK scheme effectively.

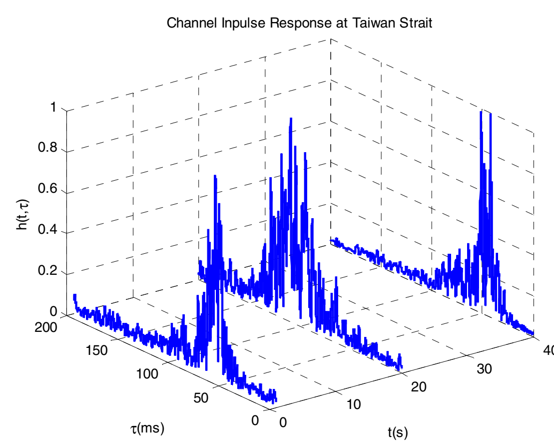
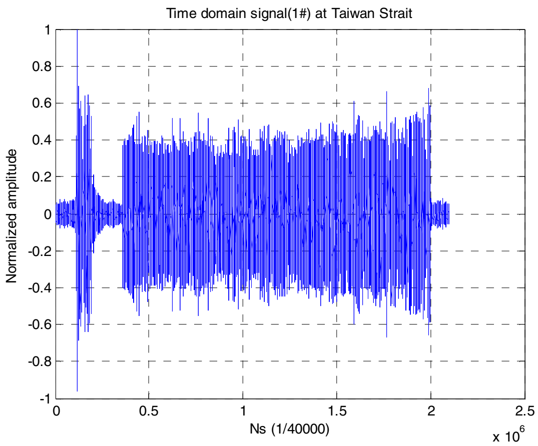
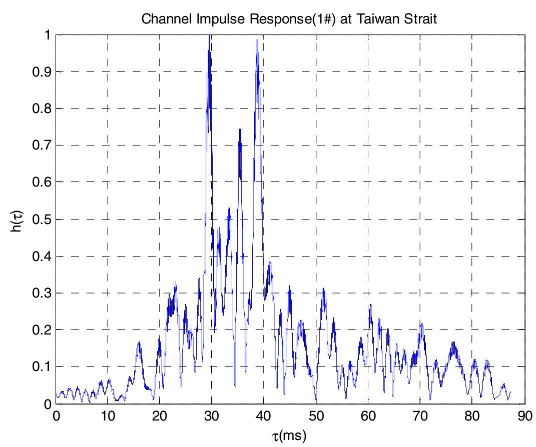



Fig.4 CIR estimations at Xiamen Port and Taiwan Strait

If individual received signal and its corresponding CIRs are concerned, it can be found that there are two kinds of typical signals in these sea trials. Fig.5 and 6 show the signals and their corresponding CIRs at Taiwan Strait. For 1# signal, high SNR and short multipath can be observed, while for 2# signal, there is low SNR and long multipath. Obviously, 2# signal is damaged greatly by the channel and its bit error rate is $4.4\times10^{-2}$, which is much higher than that for 1# signal with bit error rate $2.9\times10^{-3}$.

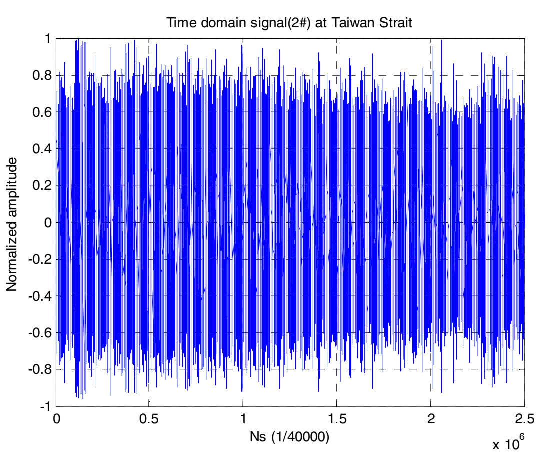



(a) Signal with high SNR

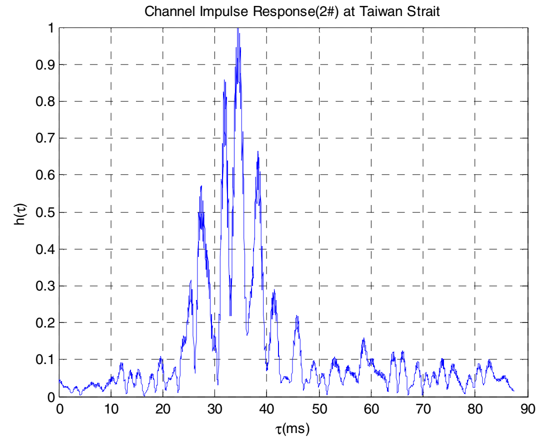



(b) CIR with long multipath

Fig. 5 Time-domain signal and CIR (1#) at Taiwan Strait




(a)Signal with low SNR




(b) CIR with long multipath

Fig. 6 Time-domain signal and CIR (2#) at Taiwan Strait

TABLE III presents the average values of bit error rate for these experiments. In order to show the performance of McH-4T4FSK scheme intuitively, we build a multi-channel 16-ary FSK (named as McH-16FSK) scheme with the same bit rate and four sub-channels. The number of transmitted data is 4096 bits so that the minimum bit error rate is $2.4\times10^{-4}$. The results showed in TABLE III indicate that McH-4T4FSK scheme exhibits lower bit error rate at Taiwan Strait. Besides, it can be seen that the bit error rate of McH-4T4FSK scheme keeps in the $10^{-3}$ level at any time. Therefore, it can be concluded that McH-4T4FSK scheme is a kind of robust communication scheme in the circumstances of high ambient noise and long multipath delay.

TABLE III. THE BIT ERROR RATE OF SEVERAL EXPERIMENTS

| Time | McH-4T4FSK | McH-16FSK |
| --- | --- | --- |
| **July 13th** | $<2.4\times10^{-4}$ | $1.2\times10^{-2}$ |
| **July 15th** | $5.5\times10^{-3}$ | $8.7\times10^{-2}$ |

## V. CONCLUSION

In summary, this paper presents a novel time frequency shift keying scheme, called McH-4T4FSK, based on four time four frequency shift keying. The proposed scheme is characterized by three merits as follows. Firstly, the scheme can greatly suppress frequency selective fading owing to the two dimension diversity of its time-frequency. Secondly, there are four sub-channels with frequency band narrower than system band at the received end, so that the SNR is higher than single channel. Thirdly, the frequency at different time slot comes from different sub-channel, which enlarges the guard space and degrades the ISI. Shallow water sea trial experiments at Taiwan Strait confirm that McH-4T4FSK has lower BER and better robustness. Therefore, McH-4T4FSK can provide a good reference for long-range UWAC.

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