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Multi-channel time frequency shift keying in underwater acoustic communication

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ABSTRACT

Current long-range underwater acoustic communication (UWAC) faces many difficulties such as great propagation loss, high ambient noise and long multi-path delay. In order to design an excellent long-range UWAC system, it is necessary to increase signal-to-noise ratio (SNR), suppress inter-symbol interference (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. Both theoretical analysis and simulation over Bellhop multi-path channel model indicate that McH-4T4FSK exhibits lower bit error rate (BER) at the same SNR compared with traditional Frequency Shift Keying (FSK) regardless of diversity or not. Moreover, shallow water sea trial experiments at Xiamen Port with 15 km distance and at Taiwan Strait with 30 km distance confirm that McH-4T4FSK possesses lower BER and better robustness.

1. 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 UWAC system [3]. Undoubtedly, how to realize remote and robust UWAC system is a pressing problem for overcoming these obstacles.

In order to get robust UWAC 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 of 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 multi-path 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 so as to effectively restrain the severe multi-path. Ref. [7] presented an optimal high speed adaptive multi-carrier UWAC system based on MFSK modulation, and relevant experiments in a lake confirmed its suitability for high speed multi-carrier UWAC system between 10 and 30 km medium range in severe acoustic channels. Considering the good performance of time frequency shift keying (TFSK) against multi-path interference, Ref. [8] explored the effect of TFSK modulation in UWAC system, and the results demonstrated its feasibility for UWAC over a distance of 5 km at a data transmission rate of 1 k 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 meaning of multi-channel is that there are multiple independent physical narrow band channel with the same bandwidth and different center frequencies at receiver. The received signal at each time slot passes the multiple channels all the same time. The

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scheme is characterized by two aspects: high-array modulation at the transmitter to improve spectral efficiency and multi-channel processing at the receiver to enhance the SNR of received signals. Hence, the UWAC system not only inherits anti-fading ability from TFSK communication system, but also can effectively extract signals from strong ambient noise due to its multiple narrow band channels.

The rest of this paper is organized as follows. In Section 2, the underwater acoustic signal propagation model is introduced. Then, Section 3 describes the novel TFSK scheme from frequency mapping, modulation and processing at receiver. In Section 4, the performance of the TFSK scheme is analyzed at Rayleigh fading channel. In Section 5, the numerical analysis results of Section 4 are provided, and meanwhile the scheme is simulated over BELLHOP multi-path channel based on beam tracing model. Furthermore, Section 6 presents sea trial results and analyzes the signals and experiment results. Finally, Section 7 summarizes this paper.

2. Underwater acoustic signal propagation model

In general, underwater acoustic signals are influenced by the ambient noise and the multi-path propagation effect. The ambient noise affects SNR directly, while the impact of multi-path propagation can result in amplitude fading and ISI 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].

Multi-path 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 the ray theory, and eigen-rays corresponding to direct or reflected multi-path can be determined using ray tracing. Considering these discrete multi-path, a time-varying channel impulse response (CIR) can be represented as:

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

where N is the number of multi-path, $a_i(t)$ is the amplitude attenuation factor of ith path and $\tau_i(t)$ is the ith path delay.

Considering the combined effects of additive noise and multi-path propagation, the signal denoted by $y(t)$ at the receiving end can be obtained through Eq. (2):

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

where $x(t)$ is the transmit signal, and $n(t)$ is the Additive White Gaussian Noise (AWGN).

When the maximum delay is shorter than the period of symbol, the channel can be regarded as Rayleigh-type fading channel. Section 4 presents the performance analysis for this kind of channel. When the maximum delay is longer than the period of symbol, the channel is a kind of complicated multi-path channel, and it is difficult to draw a closed solution in this case. In view of this, Section 5 provides the simulation results based on Bellhop channel, which is a kind of typical multi-path channel model used in UWAC system simulation.

3. McH-4T4FSK scheme

Traditionally, various techniques are used to achieve diversity effects 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 without increasing the number of antenna or dispersing transmitter power. In this section, we will introduce the system design from three aspects of frequency mapping, modulation, and processing at the receiver.

3.1. Frequency mapping

Similar to 16-ary FSK modulation scheme, the available frequency band resource is divided into sixteen frequency points. Further, these frequency points are grouped into four different physical sub-channels and there are four frequency points in each physical sub-channel. The approach brings two advantages. One is to improve the SNR of the received signals because of sub-channel's narrower bandwidth. On the other hand, the frequency points in adjacent time slots come from different physical sub-channels, as a result, the interference between adjacent time slots within a symbol could be highly suppressed. Based on the above ideas, the frequency points are noted as $f_{IJ}(1 \leqslant I \leqslant 4, 1 \leqslant J \leqslant 4)$, where J is to represent the physical sub-channel number, namely, *No. of Channel*, and I is to represent the order of frequency points within each physical sub-channel, namely, *No. in Channel.* Table 1 shows the frequency mapping f_{IJ}.

Based on the frequency mapping shown in Table 1, transmission symbols can be encoded by frequency groups, which will be described in Section 3.2.

3.2. Modulation

TFSK modulation uses signals consisting of orthogonal frequencies to denote information bits during the transmission period [12]. For example, 2-ary TFSK modulation uses 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 f_1 and the second time slot is filled with frequency f_2; when bit '1' is transmitted, frequency f_2 is transmitted firstly and frequency f_1 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. The frequency group is composed by four different frequency signals. The encoding map between symbols and frequency groups can be seen in Table 2.

The encode mapping shown in Table 2 indicates that McH-4T4FSK is characterized by the following aspects. First, each symbol has different frequency point in different time interval, which enhances the ability of anti-fading. Second, the frequency points in each symbol come from different sub-channels, which improves the capability of anti-interference within a symbol. Last,

Table 1
Frequency mapping.

No. of Channel	No. in Channel			
	$I = 1$	$I = 2$	$I = 3$	$I = 4$
$J = 1$	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}