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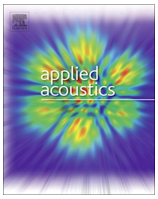

Joint virtual time reversal communications with an orthogonal chirp spread spectrum over underwater acoustic channel ☆

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ABSTRACT

In this paper, a mathematical derivation was performed to prove that there are three characteristics of chirp signals, self-compression, cyclic shift and chirp rate orthogonality. Based on these three features, a new method is proposed to improve the spectrum efficiency by joining virtual time reversal together with an orthogonal carrier. The advantages of the method can be summarized as follows. (1) By using the self-compression feature of a chirp signal, it is easy to obtain the spread gain by increasing the production of the time and bandwidth, instead of designing a complex pseudo random code. (2) The bit rate can be improved by taking the cyclic-shift feature into account and designing the M-ary modulation for the chirp carrier. (3) Chirp carriers have a certain orthogonality if they are under the considered design, that is, it is possible to use multi-carriers to improve the bit rate and spectrum efficiency. (4) Furthermore, by using the VTRM (Virtual Time Reversal Mirror) technique, the ISI (Inter Symbol Interference) of the Chirp carrier can be decreased and the robustness can be increased. Simulations, pool and sea experiments verified its feasibility and performance. Outfield experiments demonstrated that the BER (Bit Error Rate) of the method can be stabilized at a magnitude of 10^{-3} without the channel code, while the bit rate can reach 1 kbps by using a 2 kHz bandwidth. Thus, the spectrum efficiency can be over 0.5 b/s/Hz and can be useful in reality.

1. Introduction

Underwater acoustic channels (UAC) are one of the most complex channels on earth. They can be equivalent to a complex time-variant, space-variant and frequency-variant filter [1]. If signals pass though the channel, its output has non-linear and time variant changes that may cause double selective fading both in the time and frequency domains. The spread spectrum is regarded as one of the most effective techniques for conquering fading and jamming channels, such as the underwater acoustic channel, among others. It can improve the reliability of the communication system and is an optimal choice for an underwater acoustic channel. In general, there are three types of spread spectrums [2], namely: the DSSS (Direct Sequence Spread Spectrum), the FHSS (Frequency Hopping Spread Spectrum) and the THSS(Time Hopping Spread Spectrum). In recent years, because of its outstanding effect in anti-multipath and anti-Doppler, CSS(Chirp Spread Spectrum), which is based on the continuous carrier modulation with linear phase and linear frequency, has received a great deal of attention. In addition to the common features that traditional spread spectrums based on steady carriers, such as sine and cosine, have, CSS has a lower power spectral density, stronger resistance to frequency offset, longer transmission distance, and less power consumption, which make it more suitable for the underwater acoustic channel [3]. However, when it is directly used in the UAC channel, its bit rate, often a few dozen bits per second, sometimes even a few bits per second, hinder its use in a seriously bandwidth limited UAC channel. To increase the bit rate of the spread spectrum technique, M-ary and multi-carrier modulation are the primary methods that should be considered. Three categories of the method are primarily used:

(1) Using the orthogonal PN codes to carry bit information to build up a M-ary spread spectrum system. In [4], the M-ary spread spectrum is performed by PN codes to improve the spectrum efficiency. In [5], a higher data rate spread spectrum system based on orthogonal sequences was

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designed. In [6], passive time reversal DSSS underwater communication was investigated to achieve further performance enhancement via the multipath temporal-spatial focusing. Additionally, in [7], an UAC communication scheme based on M-ary bionic signal coding was proposed for high spread spectrum gain;

(2) Using the phase-shift of the PN code to carry bit information to realize the M-ary spread spectrum. A novel chaotic direct sequence spread spectrum method was proposed for secure UWA communications in [8]; a direct sequence spread spectrum based underwater acoustic communication system was proposed to reduce the system complexity and raise the communication rate [9]; a previous study [10]achieved cyclic shift keying via inserting a basis carrier(PN spreading sequence or Linear Frequency Modulation, Hyperbolic Frequency Modulation) between synchronization and data to improve system performance; this method could reduce the need for synchronization; a previous study [11] proposed a cyclic shift spread scheme that improves the communication rate and bandwidth efficiency.

(3) Combining (1) and (2) to improve the performance. A previous work [12] integrated the spread spectrum with pattern time delay shift coding based on chaotic sequences; one publication [13]proposed a scheme employing double orthogonal channel M-ary and cyclic shift keying spread spectrum communication based on gold sequences because of its large set, good self and cross correlation; to solve the problem of the low bandwidth efficiency of underwater acoustic spread spectrum communication, a multicarrier modulation scheme combined with a M-ary spread spectrum and CSK (Cycle Shift Keying) was proposed in [14]; a higher data rate spread spectrum system based on the M family phase modulation signal and N group parallel transmission was designed in [15]; a scheme for M-ary spread spectrum combined with pattern time delay shift coding for higher rates was proposed in [16]; additionally, [17] proposed a new modulation scheme that combined the advantages of time reversal and spread spectrum.

From above, the existing M-ary spread spectrum scheme was mainly designed by adding PN codes (including PN codes with cyclic shift) to improve the bit rate, and the carrier wave was mainly based on the PN code modulated by a single frequency carrier, such as a sin or cosine signal wave. However, the scheme had two faults when used for UAC channels: (1) In general, the gain of the spread spectrum mainly depended on the length of the PN code. While in the bandwidth limit UAC system, the increase of the length of the PN code meant decreasing every chip or extending the whole time of the symbol to include more PN codes in the carrier. Thus, it required a high accuracy of the spread spectrum's code catching and tracking that would result in increasing the system's complexity. (2) As we know, if the UAC channel had a serious frequency selective fading effect that was caused by the multi-path, the single frequency carrier would suffer from time-variant deep fading caused by the ISI or the Doppler, so in the end, the performance of the demodulation was influenced. One study [10]mentioned the use of the HFM (Hyperbolic Frequency Modulation) signal as the carrier in the CSK (Cyclic Shift Keying) application, but it had no further discussion or analysis on how to combine the PHY features of the chirp's signal with its application in designing the UAC system, and the main point of the paper was to focus on the method for reducing the precision requirements of synchronization. In this paper, we propose a M-ary spread spectrum based on the CSS frameworks and combine the features of the chirp carrier with the time reversal technique together to design the UAC system. Additionally, the features of the chirp signal that are based on the M-ary modulation are also proved first by mathematical derivation. Then, the principle of cyclic-shift M-ary keying based on a chirp carrier is introduced. Furthermore, simulation and analysis of the performance are performed to demonstrate the feasibility of the scheme. Finally, the experiment results that were obtained in the pool and in the sea illustrate its use in the UAC application.

2. Principle and derivation

The M-ary spread spectrum carries bit information based on the orthogonality of the PN code and requires multiple matched filters in the receiver. Such a system is relatively complex compared with the cyclic shift method, which can reduce copy numbers more efficiently. Currently, the cyclic shift scheme is mainly modulated by a single frequency carrier, such as sine and cosine waves, while the spread spectrum's gain or bit rate increase is only based on the PN code features itself. In this paper, we want to use the features of the chirp carrier itself, such as signal compression and wave cyclic-shift, instead of the PN code to achieve the M-ary spread spectrum. The VTRM method was added to the system to mitigate the effect of the ISI.

2.1. Spread spectrum feature of chirp carrier

The chirp signal is an important innovation in the radar field. In this paper, we chose the LFM (Linear Frequency Modulation) signal (p.s. HFM and other types of chirp signal could also be used in the framework) as an example to describe its spread spectrum feature. The LFM signal can be expressed as:

$$s(t) = \cos(2\pi f_0 t \pm \pi k t^2), -\frac{T}{2} \leqslant t \leqslant \frac{T}{2} \tag{1}$$

where f_0 is the centre frequency, k is the sweep rate, and T is the sweep time. If the bandwidth of the chirp signal is B, then $k = B/T$, and "$\pm k$" determines the sweep direction; when it takes a positive sign, it is 'up Chirp', otherwise, it is 'down Chirp'. The output of the matched filter is as follows [18]. In the de-spread spectrum process of the CSS, it will greatly simplify the synchronization design for using matched filters instead of the complex parts for catching and tracking the PN code compared with the traditional DSSS and FHSS. As a broadband signal, chirp carriers have a certain tolerance for the frequency offset and are robust for Doppler. In summary, it will be easier to achieve time and frequency synchronization in comparison with traditional DSSS and FHSS and will be more suitable for underwater acoustic communication.

$$\begin{aligned} r(t) &= \int_{-\infty}^{+\infty} s(t)h(t-\tau)d\tau \\ &= \int_{-T/2}^{T/2} \cos(2\pi f_0 t + \pi k t^2)\cos(2\pi f_0 (t-\tau) - \pi k (t-\tau)^2)d\tau \\ &= \sqrt{BT}\frac{\sin(\pi B t(1-|t|/T))}{\pi B t}\cos(2\pi f_0 t), -\frac{T}{2} \leqslant t \leqslant \frac{T}{2} \end{aligned} \tag{2}$$

2.2. Cyclic shift of chirp carrier

The cyclic shift keying system makes use of the autocorrelation of the PN code to achieve a cyclic shift, while the chirp signal also has good autocorrelation; therefore, if we can demonstrate its cyclic shift characteristics; then we can use this property to achieve a cyclic shift spread spectrum based on chirp carriers. As shown in Fig. 1, a whole chirp signal is divided into two fragments: fragment 1 with time duration T_p and fragment 2 with time duration $T - T_p$; the two fragments then recombine, fragment 1 and the original