

Biologically inspired covert underwater acoustic communication using high frequency dolphin clicks

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Abstract— To meet the requirements of covert underwater acoustic communication, a bionic camouflage scheme is proposed. We use sounds of marine mammals as communication signal to deceive the unintended receiver and achieve covert communication. An ultra-short duration, wide bandwidth pulse that imitates high frequency clicks of dolphin is adopted as the information carrier. We use multi-pulse modulation technique to improve anti-jamming capability. Each single pulse in the frame series which contain one bit information is modulated by the time hopping (TH) code in time domain. The frame series are modulated by pulse position modulation (PPM) technique as a whole. Transmitted reference scheme is adopted to mitigate the received signal affected by severe underwater acoustic channel. Theoretical analysis and simulation results obtained by using channel response measured at sea show that it can achieve short-range covert underwater acoustic communication benefiting from biologically inspired camouflage of communication signal.

Keywords—underwater acoustic communication; covert; dolphin clicks; time hopping; PPM

I. INTRODUCTION

Recently, there has been an increase in wireless underwater acoustic communication applications for military projects and ocean environmental monitoring. Underwater wireless transmission is prone to many security issues. Thus, many applications require robust and reliable communication with stealth. Therefore, the exploration on covert and secure underwater acoustic communication is becoming an active research topic. The core research content of joint European research project UUV covert acoustic communication (UCAC) is to establish a covert communication link between unmanned underwater vehicles(UUVs) and a distant mother platform^{[1][2]}.

The traditional covert UAC method is broadband spread spectrum technology, which reduces the average power to achieve the purpose of LPI/LPD. T.C. YANG et al adopts Direct-sequence spread spectrum (DSSS) technique to achieve LPI/LPD underwater acoustic communication between mobile or static platform^[3-4]. A pair of energy detectors that are insensitive to the phase fluctuations is proposed, whose outputs are used to determine the relationship between adjacent symbols. Good performance is achieved for a signal-to-noise ratio (SNR) as low as -10 dB based on at-sea

data^[5-6].

References [7-8] investigate covert UWA communications from a non-coherent perspective. Binary orthogonal modulation and binary differential phase-shift keying (DPSK) were addressed. Both schemes used DSSS technique and a RAKE receiver.

A multicarrier modulation scheme^[9-10] is proposed to achieve the objective of clandestine acoustic communications. The modulation consists of a single bit sequence simultaneously modulated onto multiple carriers. As all bands carry the same symbol stream, they can be adaptively combined with a multi-channel equalizer. Covert operation at low SNR is enabled by the spread-spectrum gain delivered by the adaptive combiner, a rate-1/3 turbo coding scheme, and through the use of periodic training. The proposed algorithms are tested on acoustic data from the Baltic Sea, using eight sub bands of 460 Hz each, at an effective data rate of 75 b/s. Robust receiver operation is demonstrated at overall receive SNRs down to -12 dB in three different channels, which corresponds to an SNR per bit $E(b)/N(0) = +5$ dB.

G. Leus et al considered the use of orthogonal frequency division multiplexing (OFDM) for covert acoustic telemetry^[11-12]. Frequency diversity method is adopted, modulating each band by OFDM. The system has been tested at sea in a highly time-varying environment. A total bandwidth of 3.6 kHz was divided in 16 sub bands. Data rates of 4.2 and 78 bit/s were adopted over ranges up to 52 km. At 78 bit/s, communication is successful at SNRs down to -8 dB, whereas the lower rate allows data transfer at SNRs down to at least -16 dB.

However, these techniques do not provide enough security as one can still detect the presence of these kinds of signals by long time integration techniques. One other disadvantage of these methods is that for effective concealment will need to reduce the signal transmission power to a bear minimum, which limits the communication distance. Even with the low SNR concealment, it is also very easy to detect the communication signals if a detection device is located between the transmitter and receiver.

There exists an alternative approach for covert communication besides lowering the SNR. The authors in [13]

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have used low-frequency dolphin acoustic signal as a carrier and digital modulation interval modulation (DPIM) technology to achieve the bionic covert underwater communication, it allows the bio-mimetic communication signal to be detected, but it is excluded in the process of recognition. Use of low frequency bio-mimetic signal for communication as given in [13] has one other problem associated with it. It can be detected by traditional low frequency energy detector type acoustic system from very far away distances.

In this paper, a high frequency, narrow-width, wideband pulse signal inspired by dolphin clicks is used for covert communication in order to overcome the problem of low-frequency sonar detection. The proposed bionic communication uses imitation of dolphin clicks (which are narrow pulses of broadband signal at high frequency) as an information carrier. Because of its high bandwidth narrow pulse characteristics^[14], this scheme has unique advantages in terms of signal covertness and multipath resolution capability. In this way, it is suitable for the secret underwater acoustic communication. For this scheme, the signal generation, modulation, synchronization and demodulation are different from the conventional sine-carrier modulation techniques. The paper proposes an algorithm for this scheme for combating effects of multi-path underwater acoustic channel.

This paper is organized as follows. Section II describes the covert scheme including transmission signal as well as the frame structure of the transmitter. Receiver processing to separate DSSS from whale sound and subsequent channel estimation and equalization are also a part of this section. Section III gives the simulation results of this scheme on multipath underwater acoustic channel. The paper is concluded in Section IV.

II. TRANSMITTER

A. Rayleigh monopulse

In the bionic covert communications scheme, the selection of pulse shape and its parameters are important. Because it not only affects the power spectral density (PSD) of transmitted signal, but also affects its similarity with dolphins click at high frequency signals. This paper adopts Rayleigh single pulse obtained by the first derivative of the Gaussian waveform as analog signals, and the expression is:

$$p(t) = A \frac{\sqrt{2e}}{\tau} t e^{-\left(\frac{t}{\tau}\right)^2} \quad (1)$$

Where A represents the pulse amplitude; t is time duration; τ stands for attenuation constant. The energy of a pulse mainly concentrates within the range of 5τ . The expression of frequency domain is as follows.

$$p(\omega) = A\omega\tau^2\sqrt{2\pi}e^{-\frac{\omega^2\tau^2}{2}} \quad (2)$$

In Fig. 1 the pulse width is $10\mu s$, and the 3 dB bandwidth is from 55 kHz to 170 kHz, Which is consistent with the bandwidth range of dolphins' high frequency pulse signal.

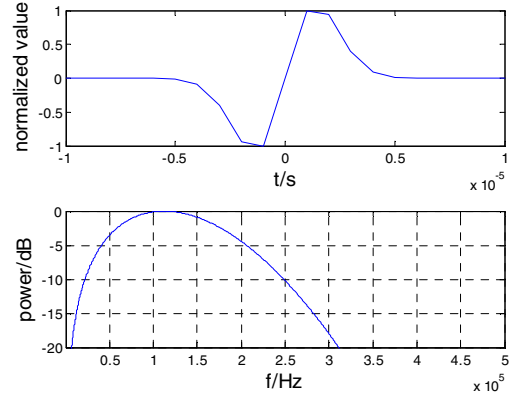


Fig. 1 time and frequency property of Rayleigh pulse

B. Bio-inspired dolphin click

From the observations made by reference [15-16], a double down chirp structure is proposed to model dolphin clicks and it is designed to reflect the frequency bandwidth of bottlenose dolphin pulses. The parameters of bio-inspired signal are shown in table 1 from reference [16] which also gives the method of two double down chirp combination.

Table 1 Bio-inspired signal set from reference16

Signal	Chirp rate	Chirp1	Chirp2
DC1	-0.420×10^6	30-114kHz	46-130kHz
DC2	-0.375×10^6	30-105kHz	55-130kHz
DC3	-0.330×10^6	30-96kHz	64-130kHz
DC4	-0.300×10^6	30-90kHz	70-130kHz
DC5	-0.270×10^6	30-84kHz	76-130kHz
DC6	-0.240×10^6	30-78kHz	82-130kHz

In this paper, a double Rayleigh monopulse structure is proposed to model dolphin click, and the synthesis signal is shown as follows.

$$s(t) = w_1 p_1(t) + w_2 p_2(t - \tau) \quad (3)$$

w represents the window function, one pulse is delayed by τ to add with the other pulse. We filter $s(t)$ to limit its bandwidth to a dedicated range. The synthesis bio-inspired waveform is shown in Fig. 2. And Fig.3 is the spectrum.

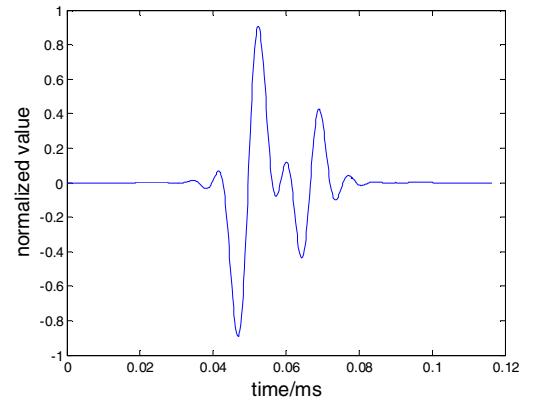


Fig. 2 synthesis signal

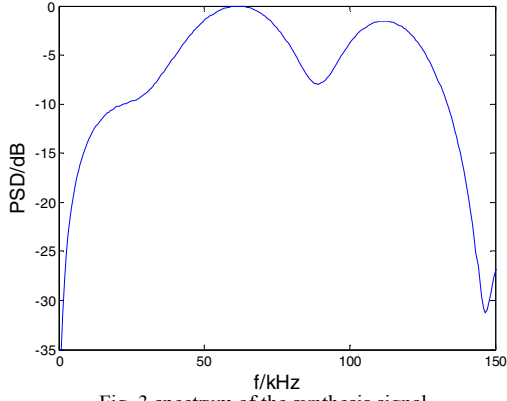


Fig. 3 spectrum of the synthesis signal

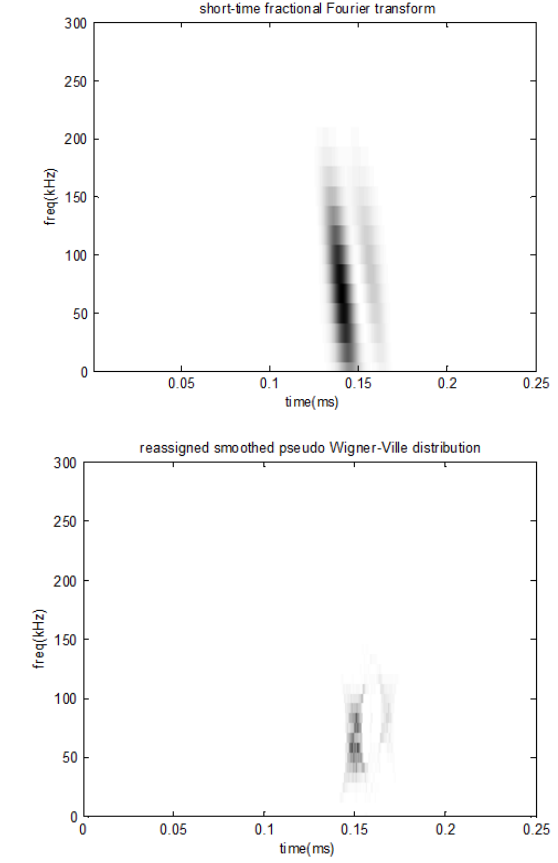
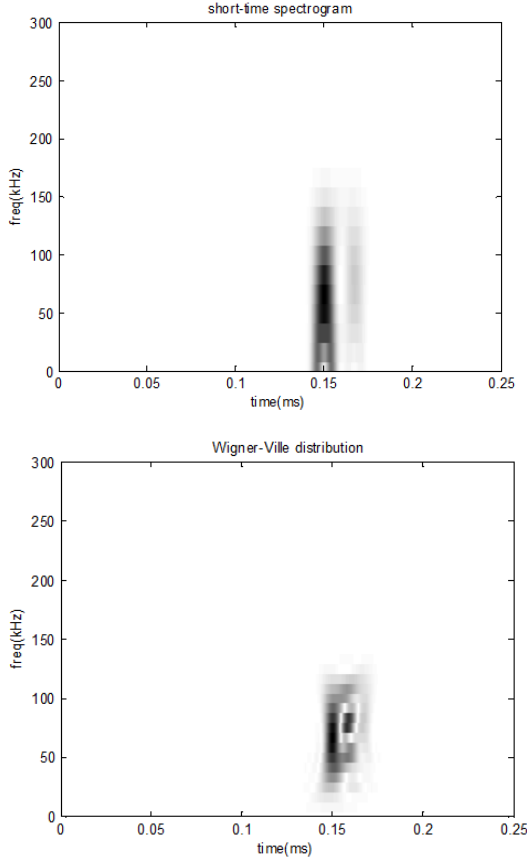


Fig. 4 time and frequency representation of the synthesis signal

C. Principle of TH-PPM-click modulation

In TH-PPM system, the duration of one bit is T_d , it is divided into N_s small time interval T_f , T_f is the interval of two adjacent pulse without time hopping. so $T_d = N_s \cdot T_f$, The structure of TH-PPM signal is described in detail in Fig. 2. The square waveform represents the information bit. So the information rate is $R_s = 1/T_d = 1/(N_s \cdot T_f)$. N_s pulses form a pulse series which represent the same information bit, in addition to the time delay of single pulse modulated by TH code, the pulse series should be modulated by PPM technique as a whole.

Within the interval $[0, T_f]$, time is divided into N_t chips, so the pulse can be hopped to the specialized position by TH code during the time of $[0, N_t \cdot T_c]$, in the above Fig $N_t \cdot T_c = T_f$. In Fig. 5, within the T_f time, there is only one pulse, with width $T_p \ll T_f$, and the signal duty cycle is small. So TH - PPM signal expression as follows:

$$s(t) = \sqrt{E_b} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_f-1} p(t - iT_d - b_i T_c - jT_f - c_j T_c) \quad (3)$$

$p(t)$ is imitated dolphin sound shaping pulse.

E_b , T_d , b_i , T_f , T_c , c_j represent the symbol energy, symbol length, the i information symbols, two adjacent pulses without hopping interval, chip length in T_f , and frequency hopping code respectively. σ is PPM modulation constant between adjacent symbols.

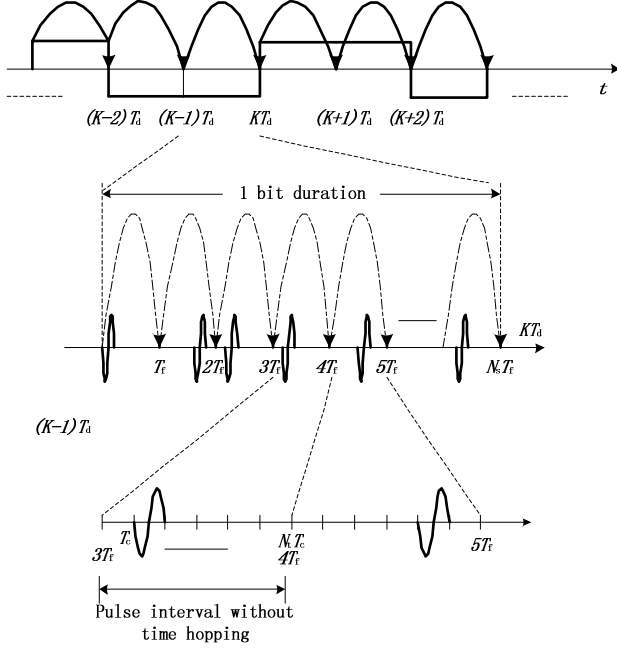


Fig. 5 structure of TH-PPM signal

III. RECEIVER

A. Principle of TH-PPM-click demodulation

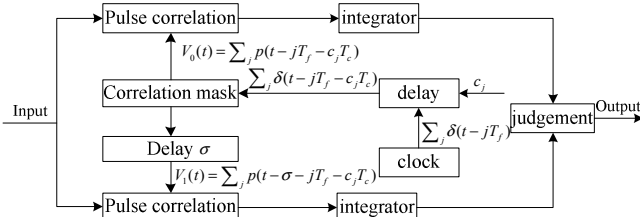


Fig. 6 demodulation diagram of TH-PPM receiver

We adopt correlation for the demodulation of TH-PPM. The process diagram is shown in Fig. 6. For simplicity of the analysis, we assume that signal has been synchronized perfectly to one code time. We correlate the received signal with the two mask signal $V_0(t)$ and $V_1(t)$ respectively, so we can get the two expressions as follows, if $z_0 \geq z_1$, the demodulation result is 0, else the result is 1.

$$\begin{cases} Z_0 = \int_{t \in T_d} r(t) V_0(t) dt \\ Z_1 = \int_{t \in T_d} r(t) V_1(t) dt \end{cases} \quad (4)$$

B. Transmitted reference scheme for TH-PPM

To mitigate the effects of underwater acoustic channel on the received signal, we use dedicated transmitted reference

frame structure as shown in Fig. 7.

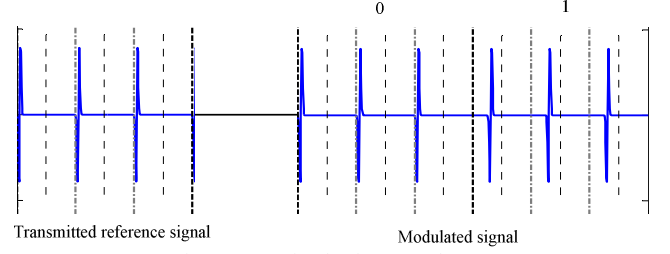


Fig. 7 Transmitted reference scheme

Conventional receiver structures for TH-PPM scheme require a locally generated copy of the received waveform. The availability of an ideal template of a received pulse guarantees the highest performance in terms of SNR at the receiver. The generation of a perfect copy of a received pulse, however, may lead to substantial increases in receiver complexity as it needs accurate channel estimation and precise synchronization. In transmitted reference schemes, a reference pulse series is transmitted before the data modulated pulse. At the receiver, each data-modulated pulse series is correlated with this reference pulse rather than a locally generated pulse copy.

IV. SIMULATION RESULTS

A numerical simulation is made to validate the feasibility of the proposed scheme. The impulse response of the channel is obtained from an experiment at sea is shown in Fig. 8.

The BER (bit error rate) performance of the proposed scheme is evaluated on both an AWGN (additive white Gaussian noise) channel and an underwater multi-path channel. The results are given in Fig. 9. The blue line shows the results of signal as it passes through AWGN channel, while the red line illustrates the performance of the proposed scheme in underwater multipath channel, whose performance is worse than AWGN channel. The multi-path channel affects it. To mitigate this, we put transmitted reference pulse in the preamble of the signal; each data-modulated pulse is correlated with this reference pulse rather than the locally generated pulse copy. The black line in figure 6 represents this. We can see the performance is better for the transmitted reference scheme.

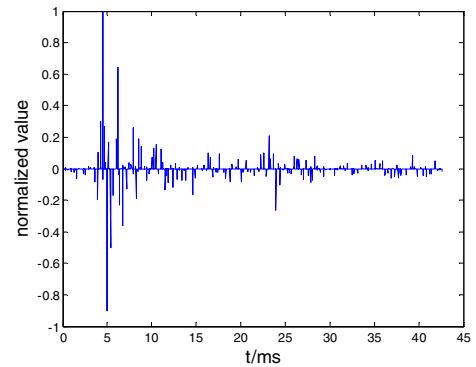


Fig. 8 channel impulse response

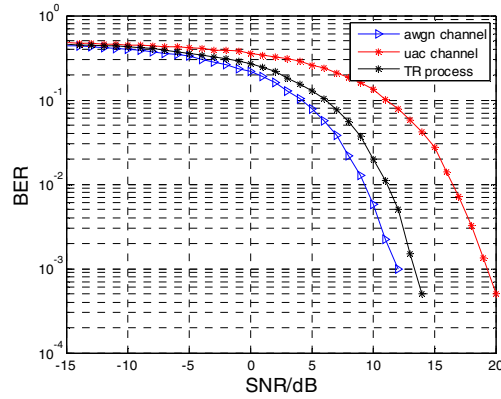


Fig. 9 simulation results

V. CONCLUSION

A covert underwater acoustic communication scheme using mimicry high frequency dolphin click is proposed in this paper. Compared with traditional covert schemes operating in low SNR with continuous sinusoid carrier modulation, we can realize LPI and LPD underwater acoustic communication not only in time and frequency domain, but also in similar sense of hearing. The mimicry method makes distinguishing communication signal from marine mammal sounds difficult for the adversary. In this way, covertness is achieved. The TH code controls the scheduling of transmitted pulse in this scheme. Only adopting the same TH code can correctly recover the modulated signal. Pseudo random nature of TH code makes the power spectral density (PSD) of the transmitted signal smooth. In frequency domain the signal is ultra-short pulse with broad spectrum and low duty cycle, which leads a extremely low PSD. Simulation results and theoretical analysis have verified the feasibility of the proposed scheme. In addition to these characteristics ultra-short pulse is also suitable for distance measurement and location finding so navigation and location finding functionality can be achieved by the same communication system.

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