Experimental demonstration of underwater acoustic communication using bionic signals

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Abstract

This paper applies dolphin whistles to covert underwater acoustic (UWA) communication and proposes a UWA communication scheme based on M-ary bionic signal coding. At the transmitter end, the scheme maps multiple information bits into a dolphin whistle through a signal selector. At the receiver end, passive time reversal mirror (PTRM) is used for channel equalization and source information is restored according to the decision of which whistle is transmitted. The scheme has high spread spectrum gain. The anti multi-path performance is greatly improved when using PTRM. Different from traditional covert UWA communication methods, this mimicked signal is unlikely to alert an adversary even in high SNRs because of its real existence in marine environment. A tank experiment is conducted for the scheme, at communication rate of 50 bit/s with SNR = 5 dB user information is recovered at a very low bit error rate. The results of tank experiment demonstrate the feasibility of this covert UWA communication scheme.

1. Introduction

With the development of modern detection technology, high requirements have been put forward for underwater warfare platform especially for covert UWA communication [1]. Bad covert performance of UWA communication could easily lead to the exposure of transmitting platforms and loses the covert advantages of underwater combat. So studies for covert UWA communication are very necessary [2].

The probability of detection and interception is proportional to signal-to-noise ratio (SNR). High signal levels expose the communicating platforms. Therefore, traditional covert UWA communication is usually conducted in lower SNR condition. But as SNR decreases, the reliability of system will reduce greatly. In order to maintain good covert communication performance even in higher SNR condition, this paper proposes a mimicry approach. Instead of simply reducing SNR, this approach aims at using a modulating waveform that appears to naturally occur in UWA environment. It can be the sound produced by dolphins, whales and other marine mammals. This mimicked version of communication signal has strong covert performance. They are unlikely to alert an adversary even if detected due to their real existence in marine environment.

Dolphin signals are generally divided into three categories [3,4]: clicks, whistles and burst pulses. In recent years, researches on dolphin signals mainly focus on clicks and whistles [5,6]. Paper [7] uses fractional Fourier transform method to analyze dolphin clicks, develops synthetic bio-inspired signal sets for dolphin based sonar and presents echo responses from calibrated spherical targets. Paper [8] examines dolphin echolocation clicks in terms of their time and frequency characteristics. The study finds that dolphins could modify outgoing clicks to identify and discriminate targets. Paper [9] adopts broadband recording systems to characterize the whistle characteristics of free-ranging Indo-Pacific humpback dolphins. It can be seen that research on dolphin bionic technology mainly focuses on the design of active sonar waveforms while studies of dolphin signals being applied to UWA communication are rare.

This paper proposes a covert UWA communication scheme based on M-ary signal coding and dolphin whistles. At the receiver end, PTRM is used for channel equalization to improve the anti multi-path performance of the scheme. The system has a strong spread spectrum gain and can effectively solve the contradiction between transmitting bandwidth and processing gain. The results of tank experiment show that the scheme is feasible.

2. Theory of M-ary bionic signal coding communication

2.1. Analysis of dolphin whistles

Dolphin whistles are mainly used for mutual contact, emotional expression between individuals or groups. Whistles are narrow-band FM signals. The duration lasts from a few hundred milliseconds to a few seconds. Fig. 1 is a period of real recorded dolphin whistles downloaded from Macaulay Library. Fig. 2 is the short time Fourier transforming result of the signal. Fig. 2 shows that...
energy of dolphin whistles is mainly concentrated in 2–8 kHz. They are suitable for long-distance transmission in water because of their low-frequency characteristic.

Dolphin whistles in Fig. 1 contain a total of 6 symbols with different information. A 40 ms signal is taken from each information symbol and donated: \( W_1(t) \), \( W_2(t) \), \( W_3(t) \), \( W_4(t) \), \( W_5(t) \), \( W_6(t) \). This paper analyzes the correlation characteristic of these signals. Table 1 lists normalized cross-correlation and auto-correlation coefficients.

According to the statistical results in Table 1, it can be seen that cross-correlation between different information symbols in the same period of dolphin whistles is very weak.

### 2.2. Principles of M-ary bionic signal coding

Dolphin whistles are narrow-band FM signals, so they do not need carrier modulating when coding. Similarly, they do not need carrier removing when decoding. The codec block diagram of M-ary bionic signal coding communication is shown in Fig. 3.

In this context, it is important to note that the energy of dolphin whistles is concentrated in a frequency range of 2–8 kHz, making them suitable for long-distance transmission in water due to their low-frequency characteristic. The signal symbols in Fig. 1 are used to convey different information, with each symbol representing a 40 ms signal. The paper analyzes the correlation characteristics of these signals, as presented in Table 1, which lists the normalized cross-correlation and auto-correlation coefficients.

According to the statistical analysis in Table 1, the cross-correlation between different information symbols within the same period of dolphin whistles is very weak.

### 2.3. Principles of TRM

Time reversal is the representation of phase conjugate in time domain. TRM [10–13] can be interpreted as spatial focusing and temporal focusing. Traditional TRM consists of a vertical array. Time-reversal channel side lobes of every sensor in the vertical array appear at different locations. These side lobes are uncorrelated while maximum values of all sensors are correlated, so the side lobes are suppressed well. But the side lobes will not be eliminated due to the bandwidth limitation. Single element TRM (STRM) consists of a single sensor. It can only use multi-path channel structure between the two nodes to achieve time focusing through the time reversal processing of channel. Compared with the vertical array processing, it loses spatial focusing gain which results in higher side lobes than the vertical array processing. But it can also

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**Table 1**

<table>
<thead>
<tr>
<th>Signals</th>
<th>( W_1(t) )</th>
<th>( W_2(t) )</th>
<th>( W_3(t) )</th>
<th>( W_4(t) )</th>
<th>( W_5(t) )</th>
<th>( W_6(t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_1(t) )</td>
<td>1.00</td>
<td>0.19</td>
<td>0.26</td>
<td>0.12</td>
<td>0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>( W_2(t) )</td>
<td>0.19</td>
<td>1.00</td>
<td>0.30</td>
<td>0.19</td>
<td>0.16</td>
<td>0.29</td>
</tr>
<tr>
<td>( W_3(t) )</td>
<td>0.26</td>
<td>0.30</td>
<td>1.00</td>
<td>0.27</td>
<td>0.19</td>
<td>0.23</td>
</tr>
<tr>
<td>( W_4(t) )</td>
<td>0.12</td>
<td>0.19</td>
<td>0.27</td>
<td>1.00</td>
<td>0.32</td>
<td>0.28</td>
</tr>
<tr>
<td>( W_5(t) )</td>
<td>0.20</td>
<td>0.16</td>
<td>0.19</td>
<td>0.32</td>
<td>1.00</td>
<td>0.37</td>
</tr>
<tr>
<td>( W_6(t) )</td>
<td>0.24</td>
<td>0.29</td>
<td>0.23</td>
<td>0.28</td>
<td>0.37</td>
<td>1.00</td>
</tr>
</tbody>
</table>
superpose multipath signals generated by the channel at the same
time and phase, compress signal in time domain, suppress inter-
symbol interference and improve SNR. For STRM, multipath could
enhance the power of focused signal. So the more complex the
channel, the more obvious the focusing effect of STRM (as shown
in Fig. 6. Fig. 6(a) without using TRM while Fig. 6(b) using TRM.
It is obvious that multipath is well suppressed when using TRM.)
Moreover, STRM simplifies the complexity of the device greatly.
Considering the benefits of simple equipment and low power con-
sumption achieved by the expense of spatial focusing gain, this pa-
per employs STRM.

Passive time reversal, that passive phase conjugate (PPC)
[14,15], estimates the channel response function using sync signal
and then reverses received signal in time domain passively. It can
compress multipath structure of the channel, suppress the channel
affect during signal transmission and realize low error demodula-
tion. Fig. 4 shows the diagram of PTRM in UWA communication
scheme.

As demonstrated in Section 2.1 that cross-correlation between
different information symbols in the same period of dolphin whis-
tles is very weak. So one of these whistles is served as sync signal
to estimate the channel in this paper.

3. Tank experiment

An experiment is conducted in a channel tank which is not an-
echoic in Harbin Engineering University in order to verify the fea-
sibility of the scheme. The channel tank is 40 m long, 6 m wide and
6 m high. The water in it is about 5 m deep. The transmitter and re-
ceiver nodes are located on two lanes. The band of the transducer is
2–8 kHz. Hydrophone and amplifier are BK8105 and BK2713. Sig-
nal amplifier and filter is PF-1U-8FA. Transducer and hydrophone
are dipped vertically.

Emission and collection devices are sound cards of two comput-
ers. The laying diagram of transducer and hydrophone is shown in

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Decoded results under different SNRs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SNR (dB)</td>
</tr>
<tr>
<td></td>
<td>nPTRM</td>
</tr>
<tr>
<td>5</td>
<td>3.33</td>
</tr>
<tr>
<td>3</td>
<td>3.45</td>
</tr>
<tr>
<td>2</td>
<td>3.50</td>
</tr>
<tr>
<td>0</td>
<td>4.00</td>
</tr>
<tr>
<td>-2</td>
<td>4.80</td>
</tr>
<tr>
<td>-5</td>
<td>5.73</td>
</tr>
</tbody>
</table>

Note: nPTRM means without using PTRM; PTRM means using PTRM.
Fig. 5, where $r$ is the distance between source and sink; $h_1$ is the depth of transducer; $h_2$ is the depth of hydrophone.

Parameters of the scheme are as follows: the sampling frequency is 48 kHz; four kinds of dolphin whistles with band 2–8 kHz and length 40 ms are used as signals. $W(t)$ is used as sync signal and served as the probe signal to estimate the channel information at the same time; transmission data is part of an image and data length is $1 \times 10^6$ bit; communication rate is 50 bit/s; the transmission signal lasts almost 201 s. It should be pointed out here that the channel in tank environment is relatively stable. But in real marine environment, the channel is rapidly changing both in time domain and frequency domain. In this condition, the duration of signal frame should be shorter. So the channel can be seen as unchanged during this small time slice.

When $r$ is 10 m, $h_1$ is 1 m and $h_2$ is 2 m, Fig. 6 shows the results of the experiments. Fig. 6(a) shows the result when using PTRM while Fig. 6(b) using PTRM.

As can be seen from Fig. 6(a) the channel of tank experiment is very complex, the maximum multi-path delay is about 20 ms. Multi-path makes the expanding signal of the previous symbol directly superimpose on the following one and produces inter-symbol interference. It will make the decoded correlation peak is not obvious and generate error bits. Fig. 6(b) shows the result when using PTRM. The passive time reversal channel has been significantly improved and multi-path channel get a certain degree of suppression. Fig. 7 takes local reference code $W(t)$ as an example and compares decoded results when using PTRM and without using PTRM. Fig. 7(a) without using PTRM while Fig. 7(b) using PTRM.

Comparing Fig. 7(a) with Fig. 7(b), the decoded correlation peaks using PTRM are more obvious than those without using PTRM and the system performance is greatly improved. The processed results of experimental data in Table 2 also verify this conclusion.

4. Conclusions

This paper proposes a new method for covert UWA communication using dolphin whistles. Dolphin whistles have a large time-bandwidth product, so it can obtain a certain processing gain when decoding. At the receiver end, PTRM is used for channel equalization and it can focus multi-path signal energy and get focus gain. The experimental results demonstrate that the scheme is capable of achieving good decoding performance in complex multi-path and lower SNR environment. Instead of simply reducing the SNR to a lower level, the scheme uses signals which exist in the marine experiment to obtain a better covert communication performance. They are unlikely to alert an adversary even in higher SNR conditions. In this way, covert communication can be realized in a longer distance with improved performance. This method can be used for underwater warfare platforms which need high requirements of covert performance.

Acknowledgements

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References