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Technical Note

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

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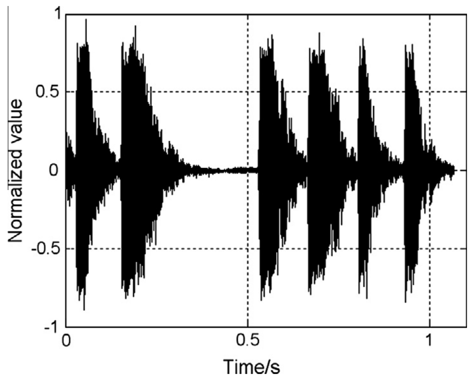

Fig. 1. Time-domain waveform of dolphin whistles.

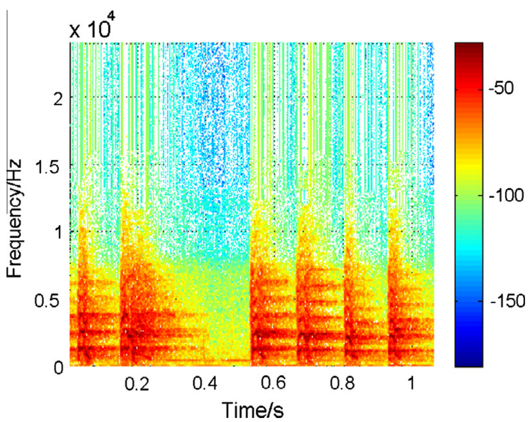

Fig. 2. Time-frequency analysis chart of dolphin whistles.

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.

Table 1
Correlation coefficients of dolphin whistles.

Signals	$W_1(t)$	$W_2(t)$	$W_3(t)$	$W_4(t)$	$W_5(t)$	$W_6(t)$
$W_1(t)$	1.00	0.19	0.26	0.12	0.20	0.24
$W_2(t)$	0.19	1.00	0.30	0.19	0.16	0.29
$W_3(t)$	0.26	0.30	1.00	0.27	0.19	0.23
$W_4(t)$	0.12	0.19	0.27	1.00	0.32	0.28
$W_5(t)$	0.20	0.16	0.19	0.32	1.00	0.37
$W_6(t)$	0.24	0.29	0.23	0.28	0.37	1.00

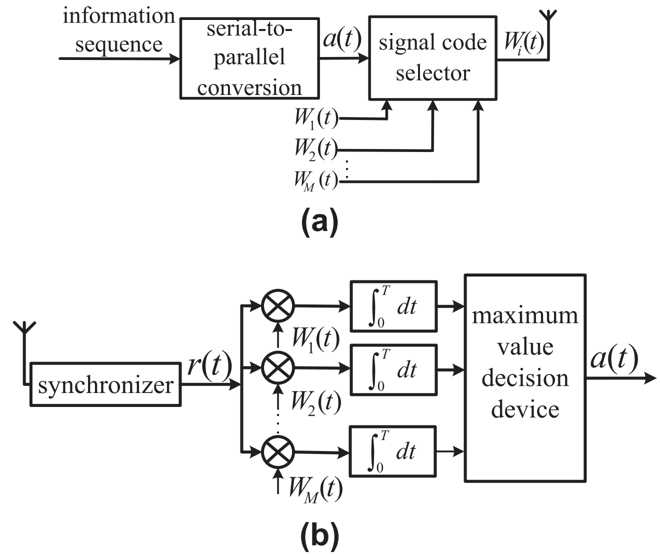

Fig. 3. M-ary bionic signal coding communication (a) the transmitter end; (b) the receiver end.

Fig. 3(a) is the block diagram of transmitter end. Serial information is transformed into parallel form and the signal selector determines which signal should be output according to the value of parallel form information.

Fig. 3(b) is the block diagram of receiver end. As shown in Fig. 3(b), the starting time base of the signal frame will be determined by the sync signal. Received signal $r(t)$ is transported into M match-filters to perform correlation calculation then the transmitted whistle will be found out. Since whistles have a good correlation characteristic, branches that are not irrelevant with the transmitted whistle will output a very small value.

It can be seen that the key point of the scheme is to guarantee good correlation performance of whistles signals. In another word, the autocorrelation peak should be sharp and the cross-correlation should be weak. Otherwise it will lead to decoded auto-correlation peaks not obvious or cross-correlation peaks too large. It will affect the decision result and generate error bits.

According to statistical analysis of dolphin whistles listed in Table 1, this paper chooses a group of signals which have small cross-correlation coefficients(normalized cross-correlation coefficients less than 0.3), that $W_1(t)$, $W_2(t)$, $W_3(t)$, $W_5(t)$ as the signals. At the transmitter end, the signal selector randomly chooses one of these signals according to the transmitted information sequence. So the information carried by each signal is $\log_2 4$, that is 2 bit.

2.3. Principles of TRM

Time reversal is the presentation 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 the 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