Mimicking Multiple Whale Whistles-Based Underwater Covert Communication

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\section*{ABSTRACT}
In underwater biomimetic covert communications, multiple whale whistles are mimicked for improving covertness. The conventional mimicking methods suffered from the trade-off between the mimicking performance and the bit error rate (BER). In this paper, we propose a continuous phase-multiple chirp modulation (CP-MCM) and a hybrid orthogonal whistle modulation (HOWM) to improve the BER and the mimicking performance of the biomimetic covert communication with the multiple whistles. The proposed CP-MCM utilizes chirp signals as the carriers of transmission symbols to mimic the frequency contour of the whistles accurately. The proposed HOWM utilizes the conventional OFDM in the overlapping whistle regions to avoid the interferences and the CP-MCM in the nonoverlapping regions to attain the large mimicking performance. Computer simulations and practical ocean experiments demonstrated that the proposed HOWM mimicked the multiple whistles with better BER performance than conventional methods.

\section*{INDEX TERMS}
Underwater communication, biomimetics, OFDM.

\section*{I. INTRODUCTION}
Underwater biomimetic covert communication methods transmit communication signals mimicking aquatic creature sounds. Even if enemies receive the biomimetic communication signals, the enemies consider the signals as the aquatic creature sounds [1]. Since the whales are worldwide distributed and their whistle sounds are reached over a long distance, the whale whistle based biomimetic covert communication methods have been researched [1]–[8].

The whale whistle patterns are characterized in the time-frequency domain, which are called a frequency contour. If the communication signals are generated with similar frequency contours to the whistles, the communication signal sounds are close to those of the real whale [1], [9]. To design the communication signal mimicking the real whale whistle, [10] proposed a chirp spread spectrum (CSS) based mimicking method that divided the whistle into multiple slots in the time domain and assigned an up/down chirp to each slot. In [9], a frequency shift keying (FSK) based mimicking method divided the whistle into multiple slots in the time domain and modulated the slots according to the center frequency of each slot. However, the transmitted signals modulated by the CSS and the FSK had different frequency contours from the real whale whistles because of the frequency discontinuities between symbols. To improve the mimicking performance, the frequency contour of the real whistles needed to be preserved for the modulated signals. In [11]–[13], the real whistles themselves were utilized for the transmitted signals as symbols. [11] classified the whistle patterns to allocate bits and detected the received whistles using machine learning. [12], [13] developed the time-frequency shift keying (TFSK) that allocated bits to the shifted time-frequency locations of the whistles. These methods had large mimicking performances but low data rates.

To increase the data rates, the phase shift keying (PSK) based mimicking methods were developed [14]–[16]. In [14], a continuously varying carrier frequency modulation (CV-CFM) generated the continuously varying frequency carriers with the same time-frequency contours of the real whistles and modulated each slot with the PSK. Since the frequency variation in a whistle was larger than the coherent bandwidth, the differential PSK (DPSK) was utilized. In general, the whales live in groups and generate multiple whistles, which are sometimes overlapped in the
time-frequency domain. For the multiple whistles, [14] suffered from the interference among the overlapped whistles and had a large BER. In [15], the orthogonal codes with the CV-CFM were utilized to mitigate the interference. However, the orthogonal code not only decreased the data rate by the code length but also did not perfectly eliminate the interference. [16] proposed an orthogonal frequency division multiplexing (OFDM) based mimicking method to avoid the interference. The OFDM divided the time-frequency domain into multiple slots and mapped the DPSK symbols to the subcarriers where the frequency contour of the real whistle existed. Since every subcarrier of the OFDM satisfied the orthogonality in the frequency domain, the interferences were avoided. However, the OFDM method had a low mimicking performance by the rectangular shape of the time-frequency region.

The CV-CFM and the OFDM had the large mimicking performance and the orthogonality, respectively, but had the large BER and the low mimicking performance, respectively. In this paper, we propose a continuous phase-multiple chirp modulation (CP-MCM) and a hybrid orthogonal whistle modulation (HOWM) that improve the mimicking and the BER performances simultaneously. The proposed CP-MCM accurately mimics the frequency contour of the whistle by using multiple chirp signals. The CP-MCM also removes the phase discontinuities between successive symbols that decreases the mimicking performance. For mimicking the multiple whistles, the HOWM combines the CP-MCM and the conventional OFDM. In the HOWM, the OFDM is utilized in the overlapping regions to avoid the interference, and the CP-MCM is used in the nonoverlapping regions to increase the mimicking performance. Computer simulations and practical ocean experiments demonstrated that the proposed method had better BER performance than the conventional CV-CFM. A spectral correlation as an objective mimicking performance [1], [10], [12]–[16] and a mean opinion score (MOS) test as a subjective mimicking performance [14], [15] exhibited that the proposed method had large spectral correlations and MOS scores.

The contributions of this paper are fourfold:

- We propose the CP-MCM, which has better mimicking performance than the conventional OFDM.
- We propose the HOWM for the multiple whistles to avoid the interference and improve the mimicking performance.
- We show that the BER performance of the proposed HOWM was better than that of the conventional CV-CFM through the computer simulations and the practical ocean experiments.
- We demonstrate that the objective and subjective mimicking performances of the HOWM were better than those of the conventional OFDM through the spectral correlation and the MOS test.

This paper consists of six sections. Sections 2 and 3 describe the system model and the proposed method, respectively. Sections 4 and 5 analyze the BER and the mimicking performances, respectively. Section 6 concludes the paper.

II. SYSTEM MODEL

Assume that a transmitter sends the mimicking signals to the receiver. The transmitted signal \(s(t)\) experiences an underwater acoustic channel \(h(t)\) and the additive Gaussian noise \(n(t)\), and the received signal \(y(t)\) is represented as

\[
y(t) = h(t) \odot s(t) + n(t),
\]

where \(\odot\) denotes a convolution operator.

Assume that \(L\) whistles are mimicked for the covert communication. The messages of the \(l\)-th whistle contain \(M_l\) binary sequence \(\mathbf{B}_l = [b^1_l, b^2_l, \ldots, b^L_m]^T\) and is modulated by the DPSK. For the simple descriptions, this paper selects the DBPSK modulation scheme. Let the first bit \(b^1_l\) be a dummy bit for the differential modulation, which is mapped to the first DBPSK symbol \(d^1_l\). The \(m\)-th DBPSK symbol \(d^m_l\) is calculated as

\[
d^m_l = b^m_l \oplus d^{m-1}_l, \quad \text{for} \quad m = 2, \ldots, M_l,
\]

where \(\oplus\) denotes a modulo-2 operator.

To transmit the symbols, the DBPSK symbols are passing through a pulse shaping filter \(f(t)\), e.g., raised cosine filter, and the pulse shaping filtered DBPSK symbol \(d_l(t)\) for the \(l\)-th whistle is given as

\[
d_l(t) = f(t) \odot \sum_{m=1}^{M_l} d^m_l \delta(t - mT_s),
\]

where \(T_s\) denotes a symbol duration.

For the covertness, the pulse shaping filtered DBPSK symbols are modulated by the proposed biomimetic method, which is described in the following section.

III. PROPOSED METHOD

This section describes the proposed CP-MCM, HOWM, and detection.

A. MIMICKING CHIRP SPREAD MODULATION

Assume that a single whale whistle \((L = 1)\) is mimicked to simply describe the proposed CP-MCM. In the conventional OFDM, the frequency contour of the mimicked signal is not continuously varying and the mimicking performance is low. Let the subcarrier frequency of the DPSK symbol be \(f^m_s\), and the bandwidth of the subcarrier be \(B_s\). The \(m\)-th OFDM symbol \((s_m(t))\) is given as

\[
s_m(t) = d_1(t) \times e^{j2\pi f^m_s t}, \quad \text{for} \quad (m - 1)T_s \leq t < mT_s.
\]

Since the subcarrier of the conventional OFDM has the one constant subcarrier frequency of \(f^m_s\), the subcarrier shape of the time-frequency region of the \(m\)-th OFDM symbol is a rectangular. Thus, the OFDM may not precisely mimic the
shape of the frequency contour of the real whale whistle. An example of the time-frequency domain of the OFDM modulated signal is displayed in Fig. 1.

To solve this problem, this paper proposes the CP-MCM that utilizes the chirp signals as the carriers of the transmission symbols. The CP-MCM divides the real whistle into $M_1$ time slots with a symbol duration $T_s$. For the $m$-th time slot $((m-1)T_s \leq t < mT_s)$, if an initial frequency $f_0^m$, a final frequency $f_1^m$, a chirp rate $a_m = (f_1^m - f_0^m)/T_s$, and an initial phase $\phi_0$ are obtained from the real whistle, the $m$-th chirp carrier can be generated. If the transmission symbol $(d_1(t))$ is allocated to the subcarrier, a CP-MCM symbol from $(m-1)T_s$ to $mT_s$ is attained. The $m$-th CP-MCM symbol $(s_c(t))$ is given as

$$s_c(t) = d_1(t) \times e^{j([\phi_m + 2\pi (f_0^m t + a_m t^2)/2]),}$$

for $(m-1)T_s \leq t < mT_s$. (5)

where $\phi_m$ denotes the initial phase of the $m$-th CP-MCM basis. Since the carrier frequency variation of the current slot is not the same as that of the previous slot, the initial phase of the current slot is different from the final phase of the previous slot. This phase discontinuity causes the impulsive sound, which degrades the mimicking performance. To remove the phase discontinuity, the initial phase to the CP-MCM carrier of each time slot needs to be set by the final phase of the previous slot. The initial phase $(\phi_1)$ of the first slot is set to zero, and the initial phase $(\phi_m)$ of the $m$-th CP-MCM carrier is derived as

$$\phi_m = \phi_{m-1} + 2\pi \left( f_0^{m-1} T_s + a_m (m-1) T_s^2 / 2 \right)$$

for $m = 2, 3, \ldots, M$. (6)

$\phi_m$ of the $m$-th CP-MCM carrier in Eq. (6) is the same as the final phase of the $(m-1)$-th CP-MCM carrier. Therefore, the phase discontinuity disappears, and the sound of the modulated signal is close to that of the real whistle. Figure 2 shows the example of the CP-MCM.

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**B. HYBRID-MULTIPLE WHISTLE MIMIC MODULATION**

If the CP-MCM mimics the overlapped multiple whistles, the interference occurs in the overlapped regions, and the orthogonality may not be kept. In this paper, to solve the interference problem, we propose the HOWM that utilizes the OFDM in the overlapped regions to avoid the interference and the CP-MCM in nonoverlapped regions to attain the large mimicking performance.

The proposed HOWM is described as follows. In Fig. 3, $L$ consecutive whistles are divided by $M$ time slots with $T_s$, and $m$ is an arbitrary slot number belonging to $[1,M]$. Let an index set of the time slots for the $l$-th whistle be $R_l = \{ R_{l,1}, \ldots, R_{l,M_l} \}$, where $M_l$ denotes the number of the time slots for the $l$-th whistle and $l \in [1,L]$. In $R_l$, assume that the index set of the overlapped time slots is $R_l^o$, and the index set of the nonoverlapped time slots is $R_l^o$.

The DPSK symbols are sequentially allocated from the first slot of the first whistle to the last slot of the last whistle. For the nonoverlapped region at the $m$-th slot of the $l$-th whistle, i.e., $m \in R_l^o$, the DPSK symbol is modulated by the CP-MCM with the initial frequency $(f_0^m)$ and the chirp rate $(a_m)$. When the $l$-th whistle is overlapped with other whistles at the arbitrary $m$-th time slot, i.e., $m \in R_l^o$, the conventional OFDM is utilized at the slot. For the modulation of the OFDM, the $m$-th slot is divided by $N$ orthogonal frequency bins with the subcarrier bandwidth $(B_s)$, and a frequency bin $(F_{m,l})$ where the real dolphin whistle exists is a candidate for the allocation of the DPSK symbol. Before the allocation to the $F_{m,l}$ bin, the allocation status of the $F_{m,l}$ bin is checked whether the bin is assigned by the previous whistles, i.e., from the first to the $(l-1)$-th whistles, or not. If $F_{m,l}$ is already allocated by the previous whistles, the bin whose frequency is the closest to the end frequency of the previous slot and the nearest frequency bin to the $F_{m,l}$ is selected, and the DPSK symbol is allocated to the bin. This is because if the slot is not allocated by the DPSK symbol of the $l$-th whistle, the discontinuity of the DPSK symbols occurs and the assumption of the constant phase between two consecutive symbols is broken. Assume that the subcarrier
frequency at $F_{m,1}$ is $f_{c}^{m}$, and the DPSK symbol for the $m$-th slot is modulated to $f_{c}^{m}$. Thus, the HOWM symbol ($s_{l}(t)$) for the $l$-th whistle can be expressed as

$$s_{l}(t) = \begin{cases} d_{l}(t - \tau_{l}) e^{j(\varphi_{m} + 2\pi f_{c}^{m} T_{s})}, & \text{if } m \in R_{l}^{o} \\ d_{l}(t - \tau_{l}) e^{j(\varphi_{m} + 2\pi (f_{c}^{m} T_{s} + \frac{d_{m-1} T_{s}}{2}))}, & \text{if } m \in R_{l}^{c} \\ 0, & \text{else if } (m - 1) T_{s} \leq t < mT_{s}, \end{cases}$$

where $\tau_{l} = (R_{l,1} - 1) T_{s}$ and $\varphi_{m}$ denotes the initial phase of each slot to remove the phase discontinuity, which is derived as

$$\varphi_{m} = \begin{cases} \varphi_{m-1} + 2\pi f_{c}^{m-1} T_{s}, & \text{if } (m - 1) \in R_{l}^{o} \\ \varphi_{m-1} + 2\pi \left( f_{c}^{m-1} T_{s} + \frac{d_{m-1} T_{s}}{2} \right), & \text{else if } (m - 1) \in R_{l}^{c} \\ 0, & \text{else.} \end{cases}$$

The HOWM signal for the $l$-th whistle is calculated by Eqs. (7) and (8). The mimicked signal ($s(t)$) in the $m$-th slot for the whole whistles is generated by combining $L$ signals and is attained as

$$s(t) = \sum_{l=1}^{L} s_{l}(t), \text{ for } (m - 1) T_{s} \leq t < mT_{s}. \quad (9)$$

In the next subsection, the detection of the proposed method is described.

**C. DETECTION**

The transmitted signals pass through the underwater channel, and are received at the receiver. The received signal is obtained by Eq. (1). Assume that the transmitter and the receiver share the frequency contour of the mimicked whistles. The received signal ($y_{l}(t)$) of the $l$-th whistle is given as

$$y_{l}(t) = y(t - \tau_{l}), \text{ for } 0 \leq t < M_{l} T_{s}. \quad (10)$$

In Eq. (10), $y_{l}(t)$ may contain other mimicked signals. Since the mimicked signals have different frequency contours, the received signal ($y_{l}(t)$) of the $l$-th whistle without interference can be obtained by multiplying the complex conjugate of the carrier for the $l$-th whistle to $y_{l}(t)$. The demodulated symbols are passing through a low-pass filter (LPF).

The baseband signal ($\hat{y}_{l}(t)$) of $y_{l}(t)$ is calculated as

$$\hat{y}_{l}(t) = \begin{cases} y_{l}(t) e^{-j(\varphi_{m} + 2\pi f_{c}^{m} T_{s})}, & \text{if } \tilde{m} \in R_{l}^{o} \\ y_{l}(t) e^{-j(\varphi_{m} + 2\pi (f_{c}^{m} T_{s} + \frac{d_{m-1} T_{s}}{2}))}, & \text{else if } \tilde{m} \in R_{l}^{c} \end{cases}$$

for $(m - 1) T_{s} \leq t < mT_{s}, \quad (11)$

where $\tilde{m} = m + R_{l,1} - 1$ and $m = 1, 2, \ldots, M_{l}$. In $\hat{y}_{l}(t)$, the received signal of the $l$-th whistle exists in the frequency range from $-B_{s}/2$ to $B_{s}/2$. Thus, the interference is removed by passing the LPF, i.e., the pulse shaping filter, and the filtered output ($\hat{\gamma}_{l}(t)$) is expressed as

$$\hat{\gamma}_{l}(t) = f^{s} (-t) \odot \hat{y}_{l}(t), \quad (12)$$

where $*$ denotes the complex conjugation.

Then, the $m$-th received symbol ($\hat{\gamma}_{m,l}$) of the $l$-th whistle is obtained as

$$\hat{\gamma}_{m,l} = \hat{\gamma}_{l}(t)|_{t = (m-1)T_{s}}, \quad \text{for } m = 1, 2, \ldots, M_{l}. \quad (13)$$

Suppose that $T_{s}$ is shorter than the coherence time, the channel does not vary during two consecutive symbols.
TABLE 1. Modulation parameters.

| Scheme | $L_c$ | $B_s$ |
|--------|-------|-------|
| CV-CFM | 1     | 200   |
|        | 3     | 200   |
| OFDM   | 1     | 200   |
|        | 3     | 200   |
| HOWM   | 1     | 200   |
|        | 3     | 400   |

For the detection of the proposed method, the differential detection is executed by multiplying the current symbol and the complex conjugate of the previous symbol. The $m$-th symbol ($\hat{d}_m$) for the detection is calculated as

$$\hat{d}_m = \hat{r}_m \left( \hat{r}_{m-1} \right)^*$$

for $m = 2, \cdots, M$. \hspace{1cm} (14)

The detection of the received symbol is conducted by the comparison of the hypotheses and is derived as

$$H_0 \left( \hat{b}_m = 0 \right) : P(\hat{d}_m | b_m = 1) < P(\hat{d}_m | b_m = 0)$$

$$H_1 \left( \hat{b}_m = 1 \right) : P(\hat{d}_m | b_m = 1) > P(\hat{d}_m | b_m = 0),$$

where $P(\hat{d}_m | b_m = 1)$ and $P(\hat{d}_m | b_m = 0)$ denote the likelihoods. \hspace{1cm} (15)

In the next section, we evaluate the BER and the mimicking performances of the proposed HOWM.

IV. EVALUATION OF COMMUNICATION PERFORMANCE

This section compares the BER performance of the proposed HOWM with the conventional CV-CFM and OFDM through the computer simulations and the practical ocean experiments.

A. MODULATION PARAMETERS OF WHISTLE MIMICKING SIGNAL

The modulation parameters of the CV-CFM, the OFDM, and the HOWM used in the computer simulations and the practical ocean experiments are displayed in Table 1. A DBPSK and a 1/3 turbo code were used.

In [15], different orthogonal codes are assigned to each whistle signal to mitigate the interference among whistles. In Table 1, $L_c$ denotes the orthogonal code length for the interference mitigation of the CV-CFM proposed in [15]. The Kasami code with a length of $L_c$ was utilized for the orthogonality with a short length. $L_c = 1$ denotes no orthogonal code, and $B_s$ denotes the subcarrier bandwidth.

B. COMPUTER SIMULATIONS

The computer simulations were conducted to compare the BER performances of the CV-CFM, the OFDM, and the HOWM. The ocean channel model was calculated by Bellhop based on the sound speed profile (SSP) in Fig 4. The calculated channel impulse response (CIR) is shown in Fig. 5. The K-factor and the Doppler shift of each path were set to 20 dB and 4 Hz, respectively.

Figure 6 shows the BER results of the conventional methods and the proposed method according to various signal to noise power ratios (SNRs). A black triangle, a blue circle, and a red rectangular denote the CV-CFM, the OFDM, and the HOWM, respectively, and a solid line and a dashed line denote the uncoded and the coded BERs, respectively.

Figs. 6(a) and 6(b) demonstrate the BERs of $B_s = 200$ Hz for $L_c = 1$ and $L_c = 3$, respectively. In Fig. 6(b), all methods attained the array gains of the orthogonal code length ($L_c$), and the BER performances were improved compared with the BERs in Fig. 6(a). The BER of the CV-CFM without the orthogonal code had an error floor at $6 \times 10^{-2}$ by the interference, but the BER of the CV-CFM with the orthogonal code was reduced to $5.5 \times 10^{-3}$ at the SNR of 10 dB by the interference mitigation. Note that the interference was not completely eliminated by the orthogonal code in the CV-CFM. However, the HOWM and the OFDM avoided the interference and had better BER performance than the CV-CFM. For the comparison of the OFDM and the HOWM, the BER performance of the HOWM was better than that of
the OFDM since the HOWM utilized the chirp basis which was more robust to the multipath fading than the constant tone basis. The coded BER of the HOWM exhibited 3 and 1 dB SNR gains compared to those of the CV-CFM for $L_c = 1$ and $L_c = 3$, respectively.

Figs. 6(c) and 6(d) demonstrate the BERs of $B_s = 400$ Hz for $L_c = 1$ and $L_c = 3$, respectively. As $B_s$ increased, each received symbol suffered from frequency selective fading, and the number of deep faded symbols increased, which led to the error propagation of the differential detection. In Figs. 6(c) and 6(d), thus, the BER performances of all methods were degraded by the frequency selective fading compared to Figs. 6(a) and 6(b) with $B_s$ of 200 Hz. Figs. 6(c) and 6(d) showed that the HOWM had better BER performances than the CV-CFM and the OFDM.

C. OCEAN EXPERIMENTS

In this subsection, the BER performances of the CV-CFM, the OFDM, and the HOWM are verified through the practical ocean experiments. The ocean experiments were carried out in the Yellow Sea of South Korea in October 2021 and were performed at a point of 12.7 km apart from Sinzindo in Fig. 7. One transmitter (Neptune-D17BB) and two receivers (TC4032) were utilized. The transmitter was dipped to 20 m, and two receivers of channels 1 and 2 were dipped to 15 m and 20 m, respectively.
In Table 2, the BER results of the practical ocean experiments were close to those of the computer simulations. For channel 1 and $B_s = 200 \text{ Hz}$, the BER of the CV-CFM was 0.1591 by the interference. However, the BERs of the OFDM and the HOWM were 0.0067 and 0.0025, respectively, by avoiding the interference. The BER of the HOWM were lower than that of the OFDM by the chirp basis. The BER of the CV-CFM with the orthogonal code was improved to 0.0274. The OFDM and the HOWM also obtained the array gain and their BERs were zeros. The practical ocean experiments also demonstrate that the HOWM had better BER performance than the CV-CFM.

V. EVALUATION OF MIMICKING PERFORMANCE

In this section, the objective and subjective mimicking performances of the proposed and the conventional methods were tested. The objective performance was evaluated by using the spectral correlation between the real whistles and the modulated signals. The subjective performance was evaluated by using the MOS test that humans scored the similarity by hearing the real whistles and the modulated signals.

A. SPECTRAL CORRELATION

The objective mimicking performances of the CV-CFM, the OFDM, and the HOWM were compared through the spectral correlation [10], [12]–[16]. The closer the correlation coefficient is to one, the greater similarity is obtained between the two signals. The correlation coefficients were calculated by $B_s$ from 50 Hz to 800 Hz and are shown in Fig. 9.

In Fig. 9, a black triangle, a blue circle, and a red rectangular denote the correlation coefficients of the CV-CFM, the OFDM, and the HOWM, respectively. The correlation coefficients of all methods were close to one when $B_s$ was less than 100 Hz. As $B_s$ became greater, the frequency contour bandwidths of the modulated signals became larger, and the correlation coefficients decreased. At $B_s$ of 400 Hz, the OFDM had the lowest mimicking performance among the three methods because the shape of the time-frequency region of the subcarrier was a rectangle. However, the HOWM and the CV-CFM had the large mimicking performances with the correlation coefficient of 0.98.

B. MOS TEST

The subjective mimicking performances of the CV-CFM, the OFDM, and the HOWM were compared through the MOS test [14], [15]. $B_s$ of all methods were set to 200 Hz, 400 Hz, and 800 Hz. 35 people from 20 to 30 years old participated in the test, and Shure SRH 840 headphone was utilized. The MOS test was executed as in [14], [15]. The subjects heard the real whistle twice and the modulated signal once. The real whistles were also tested to obtain the reference score.

Table 3 shows the grading criteria of the MOS test. Table 4 demonstrates the MOS test results. The score of the real whistle was 4.32, whereas the score of the OFDM with $B_s$ of 200 Hz was 3.25. However, the scores of the HOWM...
TABLE 3. MOS test grading criteria.

| Score | Opinion         | 5  | 4  | 3   | 2   | 1   |
|-------|----------------|----|----|-----|-----|-----|
|       | Same           | Very similar | Similar | Slightly different | Different |
| CV-CFM|                             | 200| 4.03| 400 | 3.99| 800 |
| OFDM  |                             | 200| 3.55| 400 | 3.55| 800 |
| HOWM  |                             | 200| 4.03| 400 | 3.98| 800 |

and the CV-CFM had 4.03 and 4.05, respectively, which were close to that of real whistle. This is because the proposed method utilized the subcarrier frequency varying chirp basis without the phase discontinuities.

In this section, the objective and subjective mimicking performances of the proposed HOWM and the conventional methods were compared and analyzed by the spectral correlation and the MOS test, respectively. The objective and subjective mimicking performances of the proposed HOWM showed better than those of the OFDM and were close to those of the CV-CFM.

VI. CONCLUSION

For the underwater biomimetic covert communications, we proposed the CP-MCM that utilized the multiple chirp carriers and the HOWM that avoided the interference of the multiple whistle transmission. The computer simulations and the practical ocean experiments showed that the BER performance of the HOWM was better than that of the CV-CFM and the OFDM. The mimicking performance was evaluated by the spectral correlation and the MOS test. The mimicking performance of the proposed HOWM was better than that of the OFDM, and was close to that of the CV-CFM. Thus, the proposed HOWM well mimicked the real whistles with better BER performance than the conventional methods.

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