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Underwater Biomimetic Covert Acoustic Communications Mimicking Multiple Dolphin Whistles

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Abstract: This paper presents an underwater biomimetic covert acoustic communication system that achieves high covertness and a high data rate by mimicking dolphin group whistles. The proposed method uses combined time–frequency shift keying modulation with continuous varying carrier frequency modulation, which mitigates the interference between two overlapping multiple whistles while maintaining a high data rate. The data rate and bit error rate (BER) performance of the proposed method were compared with conventional underwater covert communication through an additive white Gaussian noise channel, a modeled underwater channel, and practical ocean experiments. For the covertness test, the similarity of the proposed multiple whistles was compared with the real dolphin group whistles using the mean opinion score test. As a result, the proposed method demonstrated a higher data rate, better BER performance, and large covertness to the real dolphin group whistles.

Keywords: underwater communication; biomimetic covert underwater communication; degree of mimic

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1. Introduction

Underwater biomimetic communication ensures the covertness of communication signals by mimicking the communication signals with the sounds of underwater organisms. The underwater biomimetic communication method has been researched to overcome the large, low-probability detection problem of the conventional direct sequence spread spectrum method in underwater communication [1–7].

Mimicking the dolphin whistles is commonly used for underwater biomimetic covert acoustic communications [8–23]. The dolphin whistles have chirp-like patterns varying in time and frequency with a usable frequency bandwidth of the projector, while whales and other animals generate the sounds with a low and wide bandwidth, respectively. Thus, dolphin whistles are more adequate than other ocean animal sounds for biomimetic underwater communication. Conventional biomimetic communications have been proposed using chirp spread spectrum, frequency shift keying, differential phase shift keying (DPSK), continuously varying carrier frequency modulation (CV-CFM), and time–frequency shift keying (TFSK) that transmit bits according to the time–frequency position of the whistle or the shape of the whistle pattern [8–17]. However, since most dolphins are social animals and live in groups, they produce multiple whistles. Mimicking the multiple dolphin group sounds is necessary to increase the covertness of underwater covert communication. Thus, the conventional whistle-mimicking method has a limitation of covertness by mimicking a single dolphin whistle, not a group of dolphins, which does not reflect the ecology of dolphins living in groups. When the group dolphin whistles are used for communication, the multiple whistles may increase the data rate but cause interference among the whistles, which decreases bit error rate (BER) performance.

In this paper, we propose a method to convey information by mimicking the multiple whistles produced by a group of dolphins to increase the covertness and the data rate. Multiple whistles can be generated by simultaneously transmitting the single dolphin sounds, but these have a problem in that interference occurs between the overlapped multiple whistles, resulting in low detection performance at the receiver.

The proposed method combines TFSK and CV-CFM to achieve high covertness and a high data rate by mimicking multiple dolphin whistles and mitigating the interference caused by overlapped multiple whistles. To obtain the high transmission rate, the proposed method for the multiple whistles sequentially modulates using TFSK followed by CV-CFM. When interference occurs at the overlapped multiple whistles, the CV-CFM method with phase modulation makes it difficult to demodulate the transmitted information at the interfered whistles. To solve the interference problem, we search the interference whistle locations and utilize spread orthogonal codes on the interfered whistles to mitigate the interference so that the interfered whistle can be decoded at the receiver. In addition, interleaving is applied to further reduce the effect of the remaining interference on the whistles. Since the proposed modulation method combines two modulation techniques, the complexity of the demodulation process is large and needs to be reduced. We propose a decoding algorithm in which the two modulation schemes do not interfere with each other's decoding performance. Thus, TFSK is demodulated first to estimate the time–frequency position of the whistles, and the CV-CFM of individual whistles is demodulated.

To compare BER performance and the covertness of the proposed method, computational simulations, real ocean experiments, and mean opinion score (MOS) tests were conducted. Through computational simulations and ocean experiments, the proposed algorithm demonstrated lower BER and higher transmission rates compared to the conventional CV-CFM. The MOS test confirmed the high similarity of the proposed technique to actual dolphin whistle sounds.

The contributions of the proposed methods are as follows:

1. This paper proposes an underwater biomimetic covert communication method that mimics multiple whistles produced by dolphin groups, which offers higher covertness and data rates compared to conventional underwater biomimetic communication methods.
2. The proposed approach combines both TFSK and CV-CFM to generate multiple whistles and develops a mitigation method for interference when multiple whistles are overlapped.
3. To achieve high transmission rates, a sequential decoding method is proposed to demodulate the multiple complex whistles resulting from the combination of the two modulation schemes.
4. To evaluate the communication performance and degree of mimicking, this paper conducts computer simulations, ocean experiments, and MOS tests, and the superiority of the proposed method is proven.

2. Modulation

Most dolphins live in groups and generate multiple whistles to communicate with each other. As a result, multiple group whistles are often observed simultaneously [15–23]. To enhance the covertness of underwater biomimetic covert communication, mimicking dolphin group sounds is needed rather than mimicking conventional single whistle sounds. In this paper, the proposed underwater biomimetic covert communication method mimics the multiple whistles by combining the TFSK with the CV-CFM methods to increase the covertness and the data transmission rate while preserving the BER performance.

The conventional TFSK modulation technique involves extracting frequency contours from the original dolphin whistle, generating signals with the same frequency contour, and then shifting the whistles in the time–frequency domain to convey bits. On the other hand, the CV-CFM technique maps the bits using the divided phase-modulated symbols from the whistle frequency contour. Due to the characteristics of underwater acoustic communications, the frequency changes between symbols in a single whistle are larger than the coherent bandwidth, and non-coherent modulation such as DPSK needs to be used [24].

However, both the original TFSK and CV-CFM techniques were designed to mimic the sounds of a single dolphin. Consequently, the combination of these two methods directly leads to interference between multiple whistles, resulting in reduced detection performance due to the signal interference at the receiver. To address this limitation, this section presents a technique for combining TFSK and CV-CFM to increase the transmission rate while considering interference mitigation. For the interference at the overlapped whistles, the proposed method detects the interference locations of the whistles and mitigates interference to improve detection performance at the receiver.

The dolphin group sound in Figure 1 is an example of multiple dolphin whistles.

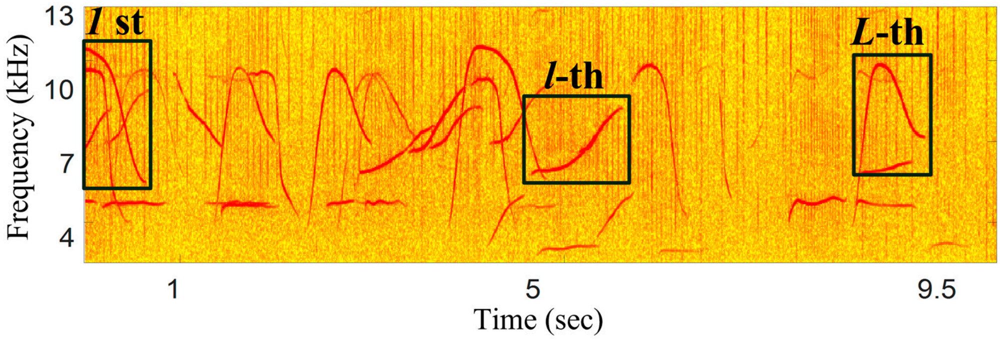

Figure 1. Whistle spectrogram of dolphins.

To mimic the multiple dolphin whistles, the proposed method employs a two-step approach. First, the individual whistle signals are modulated by the TFSK technique to allocate a portion of the transmission bits. Then, the CV-CFM is applied to allocate the remaining transmission bits. Since the bits are simultaneously allocated to TFSK and CV-CFM, this approach increases the data transmission rate compared to either of the two transmission methods. The block diagram of the proposed method is shown in Figure 2.

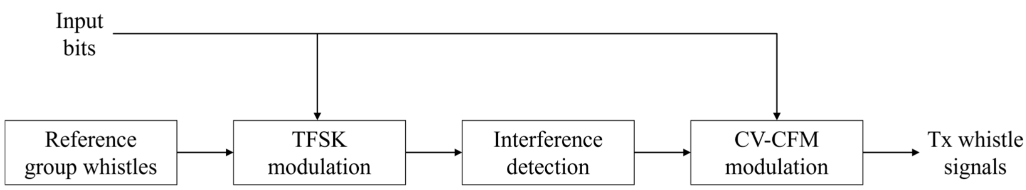

Figure 2. The block diagram of the proposed method.

In this paper, the proposed method mimics L-multiple biomimetic whistles to generate multiple whistles. For mimicking multiple dolphin whistles, the TFSK modulation technique is first applied to each whistle signal, followed by the CV-CFM modulation. Assume that the frequency change function over time for the l-th ($1 \leq l \leq L$) whistle is denoted as $f_l(t)$ [12], and the modeling of the l-th individual whistle is expressed as:

$$w_l(t) = \cos[\int f_l(t)dt]. \tag{1}$$

Figure 3 shows an example of the proposed modulation technique when TFSK is applied to a single whistle. To achieve the modulation described in Equation (1) for the multiple whistles, phase modulation and time–frequency shift modulation are applied to the individual whistle signal, denoted as $w_l(t)$. In Figure 3, it is assumed that one-time and one-frequency shift units are denoted as Δt and Δf, respectively. The total numbers of time and frequency grids are assumed to be M and N, respectively. If b_M and b_N are calculated by $log_2 M$ and $log_2 N$, respectively, a sum of b_M and b_N bits is transmitted using the TFSK method. The arbitrary time–frequency modulated signal ($x_l^{'}(t)$) of the l-th whistle is obtained by shifting $w_l(t)$ by $m'\Delta t$ and $n'\Delta f$, respectively.

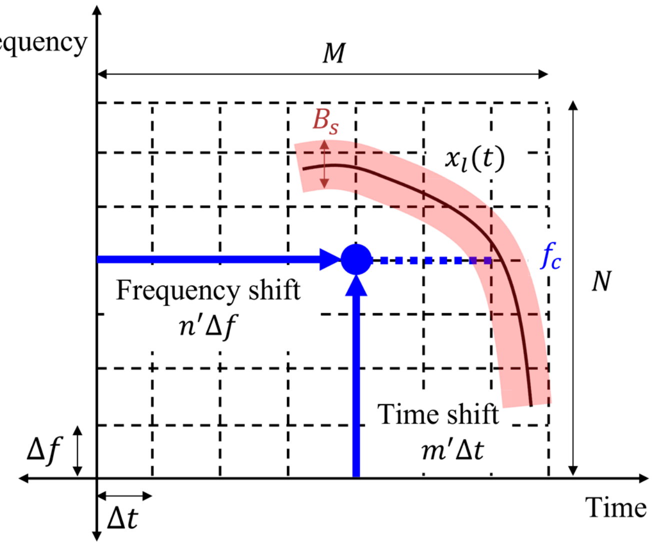

Figure 3. An example of the proposed method (an individual whistle).

When TFSK and CV-CFM are combined, the Δt and Δf requirements of TFSK need to be derived to reduce detection errors during CV-CFM decoding. The one-frequency shift (Δf) of TFSK should be larger than the frequency spread (B_s) caused by CV-CFM to avoid overlapping frequency ranges between whistles and to ensure orthogonality. Thus, the value of Δf needs to be more than twice that of B_s, considering the overlapping intervals between whistles. This can be expressed as:

$$B_s \times 2 \leq \Delta f. \tag{2}$$

To determine the requirement of Δt for the TFSK modulation, the phase modulation of CV-CFM is considered. The requirement of Δt is derived based on the property that when two signals with different phases are demodulated at the receiver, their cross-correlation converges to zero [25,26]. In the case of CV-CFM applied to a whistle, the phase changes every t_s, which is a unit symbol for time of CV-CFM. For the overlapping intervals between whistles, if a time shift of two times t_s is applied, the whistle at the original position without time shift will have a different phase from the shifted whistle, resulting in a cross-correlation of zero. Therefore, the value of Δt that satisfies orthogonality between symbols during time shift modulation is given by the following equation:

$$2t_s \leq \Delta t. \tag{3}$$

The TFSK-modulated l-th whistle, denoted as $x_l^{'}(t)$, is shifted by the product of the arbitrary m' and n' values with Δt and Δf, respectively. Therefore, $x_l^{'}(t)$ is expressed as:

$$x_l^{'}(t) = \left[\delta\left(t - m'\Delta t\right) \otimes w_l(t)\right] \times e^{j2\pi n'\Delta f t}, \tag{4}$$

where $\otimes$ denotes a convolution operation. Using the single whistle in Equation (4), L whistles are shifted to their original positions by $\mathbf{T}_l^w = \begin{bmatrix} T_1^w & \cdots & T_l^w & \cdots & T_L^w \end{bmatrix}^{\mathrm{T}}$, and we add them together. Then, the TFSK-modulated whistles $z(t)$ with L whistles become the dolphin group sound and are expressed as:

$$z(t) = \sum_{l=1}^{L} x_l^{'}\left(t - T_l^w\right), \tag{5}$$

where $z(t)$ includes interfered multiple whistles in the time–frequency domain.

The CV-CFM modulation method for individually modulated TFSK whistles is presented. Due to the characteristics of underwater acoustic communications, the frequency changes between symbols in a single whistle of CV-CFM are larger than the coherent bandwidth, and the conventional coherent modulation at the transmitter is inapplicable [12,21]. For simple demodulation, non-coherent modulation schemes such as differential binary phase shift keying (DBPSK) are used, which utilize the phase difference between two adjacent symbols.

In Equation (5), when interference occurs, the detection performance at the receiver decreases. This paper proposes a modulation method to detect interfered whistles and mitigate the interference by using the orthogonal codes during overlapped CV-CFM modulation. The orthogonal codes are used only for CV-CFM modulation in the interfered whistles, while they are not used for the non-interfered whistles.

For mitigating the interference when TFSK-generated whistles are overlapped, the proposed interference detection method utilizes energy detection in that the energy of the overlapping part of the contour of an individual whistle is larger than that of non-overlapped whistles. An example of energy when individual whistles are overlapped and interfered with by two dolphin whistles is shown in Figure 4. In Figure 4, the red line represents the l-th whistle, and the red rectangular background represents the energy of the l-th whistle. The blue line represents the $(l+1)$-th whistle, and the blue rectangular background represents the energy of the $(l+1)$-th whistle. The orange rectangular background shows the energy of the overlapped whistles.

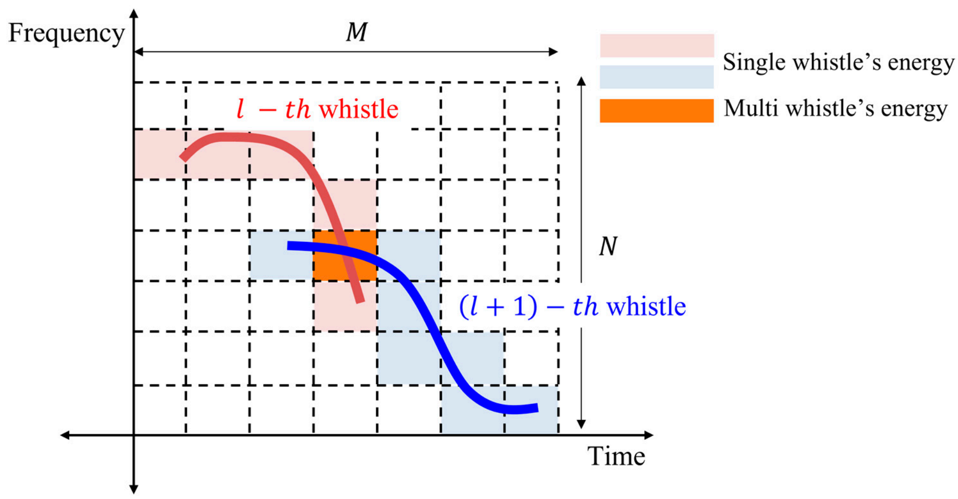

Figure 4. An example of energy comparison to find overlapped whistles.

For energy detection, assume that the two-dimensional value of time–frequency by STFT in Equation (4) is $(\mathbf{S}'(\tau,\omega))$, where τ represents a time and ω is a frequency, and the signal strength of a single signal $x_l'(t)$ in Equation (4) is E. Assume that the time position of the l-th original whale whistle is T_l^w and the time length of each whistle is L_l. Then, by comparing the value of $\mathbf{S}'(\tau,\omega)$ with E, the location of the interfering signal can be easily found. If H_0 is the interfered whistle and H_1 is the non-interfered whistle, the interference detection criteria are expressed as follows:

$$\begin{cases} H_0 : \int_{\min f_l(t)}^{\max f_l(t)} \int_{T_l^w}^{T_l^w+L_l} \mathbf{S}'(\tau,\omega)\, d\tau\, dt > E \\ H_1 : \int_{\min f_l(t)}^{\max f_l(t)} \int_{T_l^w}^{T_l^w+L_l} \mathbf{S}'(\tau,\omega)\, d\tau\, dt = E \end{cases}. \quad (6)$$

If no interference (H_1) at the l-th whistle occurs, the whistle is modulated as the conventional CV-CFM. $K-1$ information bits $(\mathbf{B}_l = [b_1,\ldots,b_k,\ldots,b_K]^T)$ are transmitted. Note that the first bit (b_1) as a dummy bit for differential modulation is allocated to the first

DBPSK symbol (s_1). The k-th symbol (s_k) is represented as in Equation (7) and the symbol transmitted at the l-th whistle is $\mathbf{S}_l = [s_1, \ldots, s_k, \ldots, s_K]^T$.

$$s_k = (b_k + s_{k-1})\ mod\ 2,\ for\ k = 2, \cdots, K. \quad (7)$$

If the l-th whistle is overlapped, i.e., interfered (H_0), the proposed CV-CFM that mitigates the interference by interleaving with an orthogonal code is utilized. If the length of the orthogonal code is L_c, the orthogonal code ($\mathbf{C}_l = [c_1, \ldots, c_{l_c}, \ldots, c_{L_c}]^T$) is used to modulate the l-th whistle where the interference occurs. The spread symbol $\boldsymbol{S_l}$ with $\mathbf{C}_l$ is defined as $\mathbf{S}_l^{sp} = \left[s_1, \ldots, s_{K/L_c}\right]^T$.

When the interference occurs, the interference is concentrated on a part of a symbol. Since the overlapped length of the interfered whistles is short enough to mitigate the interference, the interference may not be completely erased. If the interleaving is applied to the symbols in an interfered whistle $\mathbf{S}_l^{sp}$, the effect of the interference is spread over, which improves the interference mitigation performance. Assume that the interleaved symbols are denoted by $\mathbf{S}_l^{int} \in \mathbb{R}^{K/L_c}$. The l-th proposed modulated whistle $x_l(t)$ with the interference mitigated CV-CFM to the TFSK in Equation (4) is represented as:

$$x_l(t) = \left[\left(\delta\left(t - m'\Delta t\right) \otimes w_l(t)\right) + s_k\right] \times e^{j2\pi n'\Delta f t} \begin{cases} if\ H_0, & s_k \in \mathbf{S}_l^{int} \\ if\ H_1, & s_k \in \mathbf{S}_l \end{cases}. \quad (8)$$

If all L whistles are moved to the original whistle position $\left(\mathbf{T}_l^w\right)$ and added together, the multiple whistle signal that mimics the group dolphin whistles proposed in this paper is represented as:

$$S_{prop}(t) = \sum_{l=1}^{L} x_l\left(t - T_l^w\right). \quad (9)$$

The following section describes how to demodulate the proposed modulation signal $S_{prop}(t)$ consisting of TFSK and CV-CFM with interference mitigation methods.

3. Demodulation

In this section, the demodulation process of multiple whistles modulated by TFSK and interference-mitigated CV-CFM is described. To simultaneously demodulate the TFSK and CV-CFM, the complexity of the demodulation increases due to the numerous decoding possibilities. Thus, we propose a simple sequential demodulation approach.

To determine the decoding sequence of TFSK and CV-CFM, it is preferable to demodulate one method first in a way that is not influenced by the other decoding method. In the proposed dolphin whistle mimicking method, it is necessary to demodulate the TFSK signal first because the CV-CFM demodulation cannot be executed without knowledge of the time–frequency shifted positions of the whistles. When two modulation techniques are simultaneously demodulated, the searching space of the demodulation is given as $M \times N \times K$, while the sequential detection provides only $(M \times N) + K$.

If the whistle information modulated by TFSK is obtained, the phase-modulated bits of CV-CFM can be detected. The structure of the proposed receiver demodulation block is shown in Figure 5.

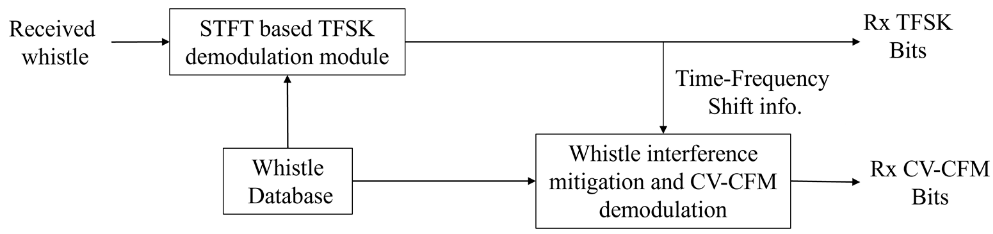

Figure 5. The block diagram of the proposed demodulation method.

First, the method for TFSK-modulated bits is described. The conventional TFSK demodulation method used a maximum likelihood (ML) detection approach in that the conjugates of all possible TFSK-modulated whistles are multiplied by the received whistles. The detection rule is to select the largest energy at a point in the time–frequency shift. However, since the received whistles are modulated by the PSK in CV-CFM, the conventional demodulation method cannot be utilized.

Therefore, this paper proposes a time–frequency energy detection method that is not affected by the phase modulation of CV-CFM. In the proposed approach, the received signal is transformed into the 2D time–frequency domain using the short-time Fourier transform (STFT), and the value of each bin in the time–frequency domain is squared to obtain the energy. As a result of the energy calculation, the values of the bins are not affected by the phase modulation. By comparing the whistle contour energy of the generated whistle at the receiver with that of the received signal, the TFSK-modulated whistle that has the closest energy contour to that of the generated whistle is determined.

The received dolphin signal ($y(t)$) is obtained by assuming that the transmitted signal ($S_{prop}(t)$) passes through the underwater channel ($h(t)$). This can be represented by :

$$y(t) = h(t) \otimes S_{prop}(t) + n(t), \tag{10}$$

where $n(t)$ denotes the underwater background noise.

Let the energy values of the received whistle ($x_l(t)$) be $\mathbf{X}_l \in \mathrm{I}^{M \times N}$ and let the energy values of the whistle ($w_l(t)$) generated at the receiver based on $\mathbf{T}_l^w$ be $\mathbf{W}_l \in \mathrm{I}^{M \times N}$. The time interval resolution of the STFT is assumed to be t_s and the frequency resolution is assumed to be B_s. The window length and the discrete Fourier transform shift interval are set accordingly to ensure that both $\mathbf{X}_l$ and $\mathbf{W}_l$ have the same intervals in the time–frequency bins [27]. Then, $\mathbf{W}_l$ is shifted by the time–frequency modulation, $m'\Delta t$ and $n'\Delta f$, with M and N, respectively. The TFSK modulation indices m and n can be found when the time–frequency contour energy distribution of the received $\mathbf{Y}_l$ is the closest distribution of the l-th whistle $\mathbf{X}_l$, which is given as:

$$TFSK(m, n) = \arg\min_{m,n}(W_l(m, n) - \mathbf{Y}_l). \tag{11}$$

After the TFSK demodulation, the receiver has the time–frequency shift information of each whistle and proceeds to decode the phase-modulated values of the CV-CFM. Since the spread and the non-spread CV-CFM to the whistle are used in the presence of interference, different demodulation schemes need to be used whether the interference exists or not.

For the detection of the interfered whistle at the receiver, the energy detection method in Equation (6) is used: If the TFSK modulated positions have been identified for L whistles, the L whistles are generated to reconfigure the received whistles. The time—frequency domain energy of these generated whistles is then calculated. If the energy of the whistles is greater than others, the whistles are considered overlapped whistles, i.e., interfered whistles. For the interfered whistle demodulation, the despreading is executed using the known orthogonal code. For whistle demodulation without interference, conventional CV-CFM phase demodulation is applied. This process is shown in Figure 6.

To demodulate the phase-modulated bits of CV-CFM at the receiver, the l-th individual whistle is extracted from the received dolphin whistle $y(t)$ using the TFSK demodulation results of Equation (10). This extraction process obtains the received individual whistle $\hat{y}_l(t)$ as:

$$\hat{y}_l(t) = |h(t)| \cos(2\pi \int f_l(t)dt + s_k + \theta_h) \times e^{j2\pi n' \Delta f t} + n(t), k = 1, \ldots K. \tag{12}$$

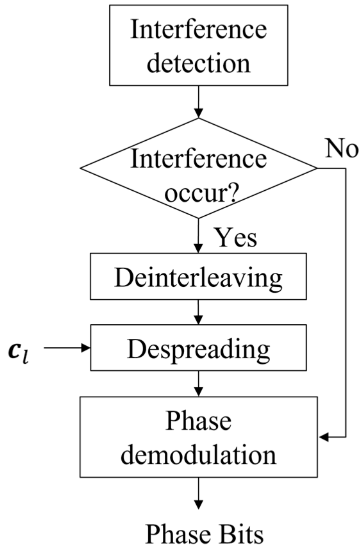

Figure 6. Despreading phase demodulation method.

The received extracted single whistle is multiplied by the complex conjugate of the frequency-shifted $w_l(t)$, denoted as $w_l^*(t) \times e^{-j2\pi n' \Delta f t}$ in Equation (12), and the low-pass filtering is executed. Then, the whistle signal modulated by CV-CFM becomes a conventional baseband phase-modulated signal. The phase information of CV-CFM can be obtained as follows:

$$r_k = |h| \cos(s_k + \theta_h) + \hat{n}, k = 1, \ldots K \tag{13}$$

In the case of whistles without interference (H_1), the symbols are demodulated by a conventional differential detection method. $\angle r_k$ in Equation (13) represents the phase information of the k-th interval of the whistle. The K phase values on the l-th th received whistle are calculated as $\hat{\mathbf{S}}_l = [\angle r_1, \ldots, \angle r_k, \ldots, \angle r_K]$. Since the CV-CFM utilizes DBPSK, conventional differential detection can be used for detecting the K-1 transmitted bits.

For the interference case (H_0), the transmitted signal is detected by deinterleaving and despreading the bits obtained by differential detection. The obtained phase value $\angle r_k$ from the interfered whistle is the result of the multiplication between the code (c_{l_c}) and the transmitted symbol (s_k). Therefore, the transmitted symbol $(\hat{\mathbf{S}}_{sp\_int})$ is obtained by multiplying the deinterleaved symbol by $\mathbf{C}_l$ for despreading as:

$$\hat{\mathbf{S}}_{sp\_int} = [c_1, \ldots, c_{L_c}] \times \begin{bmatrix} c_1 \times s_1 & \cdots & c_1 \times s_{\lfloor \frac{K}{L_c} \rfloor} \\ \vdots & \ddots & \vdots \\ c_{L_c} \times s_1 & \cdots & c_{L_c} \times s_{\lfloor \frac{K}{L_c} \rfloor} \end{bmatrix} = \left[\sum_{l=1}^{L_c} c_l{}^2 \times s_1, \cdots, \sum_{l=1}^{L_c} c_l{}^2 \times s_{\lfloor \frac{K}{L_c} \rfloor} \right] \tag{14}$$

Since c_{l_c} takes a value of 1 or -1 in Equation (14), the value of $\sum_{l_c=1}^{L_c} c_{l_c}{}^2 \times s_k$ is equal to $L_c \times s_k$. When spreading is used, an additional SNR gain of L_c is obtained compared to the case without spreading. This gain helps to mitigate inter-symbol interference.

The data rate of the proposed technique without interference is calculated as follows: the transmission bits of TFSK by time-shifting and frequency-shifting are $[log_2 M]$ and $\left[log_2 \frac{Bw}{\Delta f}\right]$, respectively. The total TFSK transmission bits per whistle are given as $\left(\left[log_2 \frac{Bw}{\Delta f}\right] + [log_2 M]\right)$. Let f_{max} be the maximum modulation bandwidth that preserves the DoM, and let the average length of a whistle be L_w. The maximum number of symbols in CV-CFM is calculated as $K = f_{max}L_w$. Therefore, the transmission rate of the proposed method is obtained as follows:

$$Data\ rate\ w/o\ interference = \frac{\left(\left[log_2 \frac{Bw}{\Delta f}\right] + [log_2 M]\right) + f_{max}L_w}{L_w + M\Delta t}. \quad (15)$$

However, if whistles are overlapped and a spreading code is used, the data rate needs to consider the data rate of the interfered whistle case. Since the spreading code length is L_c, the maximum number of symbols by CV-CFM is calculated as $K = f_{max}L_w/L_c$.

Assume that the average number of whistles per hour in a dolphin whistle is p and the probability of whistles with interference is q. The number of whistles without interference is obtained as $p(1-q)$ and the number of whistles with interference is given as pq. Therefore, the total transmission rate of the proposed method is attained as follows:

$$Data\ rate = p(1-q)\frac{\left(\left[log_2 \frac{Bw}{\Delta f}\right] + [log_2 M]\right) + f_{max}L_w}{L_w + M\Delta t} + pq\frac{\left(\left[log_2 \frac{Bw}{\Delta f}\right] + [log_2 M]\right) + \frac{f_{max}L_w}{L_c}}{L_w + M\Delta t}. \quad (16)$$

This section has described the method for detecting transmitted bits for TFSK and interference-mitigated CV-CFM.

4. Analysis of Experimental Results

In this section, the BER performance of the proposed method was compared to conventional methods through computational simulations and real ocean experiments using underwater channels. Finally, the MOS test was performed to evaluate the similarity of the bio-mimicking signals generated by the proposed method to actual dolphin whistle sounds.

4.1. Computer Simulations and Ocean Experiments

To demonstrate the communication performance of the proposed method, the whistles of Delphinus Delphis in Figure 1 were mimicked [28]. For comparing the data rates, the proposed method and the conventional methods of the CV-CFM of [12] and the TFSK of [13] were compared. Since the proposed and conventional methods utilized multiple overlapped whistles and a single whistle, respectively, the parameters of the proposed and conventional methods were different.

For the proposed method, the number of total mimicked whistles was 116, where each of the 116 whistles was phase-modulated with a symbol bandwidth (f_m) of 300 Hz for CV-CFM. The Δf in Equation (2) and Δt in Equation (3) for TFSK were obtained to be 67 ms and 600 Hz, respectively. Given the whistle bandwidth of 7 kHz, 11 segments were set for the frequency shift modulation with three-bit modulations. M was set to be two to achieve the maximum transmission rate of one bit per time symbol. Since the performance of the proposed technique varies with the spreading code length, experiments were conducted with the spreading code lengths of two, three, and four. The parameters used for the simulation of the proposed method are shown in Table 1.

Table 1. The parameter for the proposed method.

Hyperparameter	Value
Carrier frequency	16 kHz
Bandwidth	7 kHz
f_m	300 Hz
Δf	600 Hz
Δt	67 ms
The number of time, freq segments for TFSK	11, 2
Spreading code length	2, 3, 4

For the conventional TFSK of [13], Δt was set to 11 ms and Δf was set to $1/L_w$, where L_w was the average whistle length of 0.39 s with 2.5 Hz. Given the frequency range of

7 kHz, the number of frequency bins (N) was set to 2730. Thus, for each whistle symbol, 11 bits for frequency and 1 bit for time delay were transmitted, resulting in a total of 12 bits per symbol. For the conventional CV-CFM, the symbol bandwidth was set to be 300 Hz.

When the Delphinus Delphis whistle sounds were utilized for one minute and 10 s, the data rates for each technique are shown in Table 2.

Table 2. The number of bits for bio-mimetic modulation scheme.

Demodulation Scheme	Data Rate (bps)
CV-CFM, Ref. [12]	309.3
TFSK, Ref. [13]	18.2
The proposed method L_c : 2	288.9
The proposed method L_c : 3	284.1
The proposed method L_c : 4	278.9

When the proposed method utilized L_c of two, three, and four, the transmission rates decreased by approximately 6.6%, 8.1%, and 9.9%, respectively, compared to the conventional methods [12]. The transmission rate of the proposed method was 15 times larger than that of [13].

The BER performances were compared in three different environments using an additive white Gaussian noise (AWGN) channel, modeled underwater channels, and real ocean experiments. Among the compared methods, the conventional method [13] was not adequate for normal communication due to its lower transmission rate. Therefore, the comparison between [12] and the proposed method was executed.

The theoretically calculated BER in AWGN and the computer-simulated BER are displayed in Figure 7.

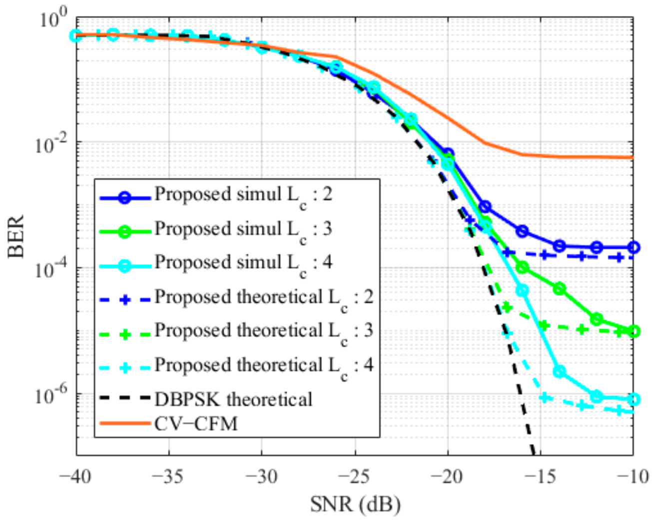

Figure 7. The simulation and theoretical BER results.

In Figure 7, the dotted lines denote theoretically obtained BERs, while the solid lines represent BERs obtained by Monte Carlo simulations. The conventional method in [12] exhibits an error floor at a BER of 10^{-2} due to inter-whistle interference. For the proposed method, however, the error floors occur at lower BERs of 10^{-4}, 10^{-5}, and 10^{-6}, when L_c was two, three, and four, respectively. If a target BER is set to be 10^{-5}, which is a typical BER, the optimal code length of the proposed method is three. Thus, the BER results of the AWGN simulation exhibit that the proposed scheme has the lowest BER with a better data rate.

For the comparisons of the BER performance through the modeled underwater channel, the Bellhop tool generated the channel model at a point in the Korean West Sea. The maximum Doppler shift of the modeled channel was 2 Hz. The delay profile and sound speed profile (SSP) used to model the channel are shown in Figure 8.

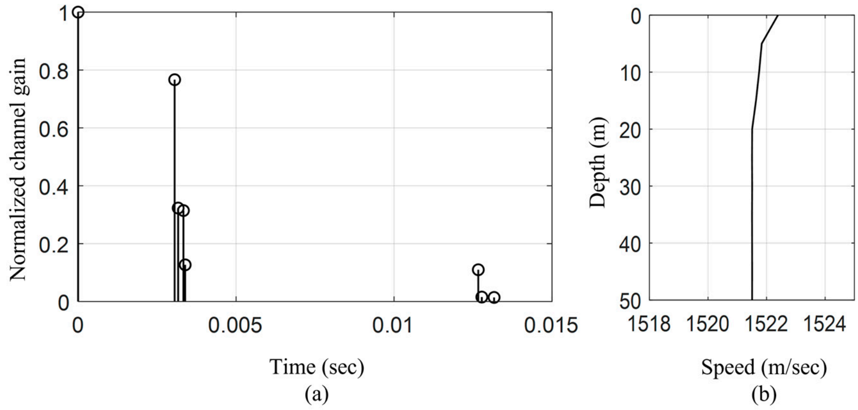

Figure 8. The simulation channel (**a**) delay profile, (**b**) SSP.

The modulation parameters for the proposed method and the compared conventional methods were the same as in AWGN channel simulations, and the L_c was set to 3. All compared methods were tested with and without using a 1/3 turbo code. The transmission rates for each scheme were the same as in Table 1. The BER results in the modeled underwater channel environments in Figure 8 are shown in Figure 9.

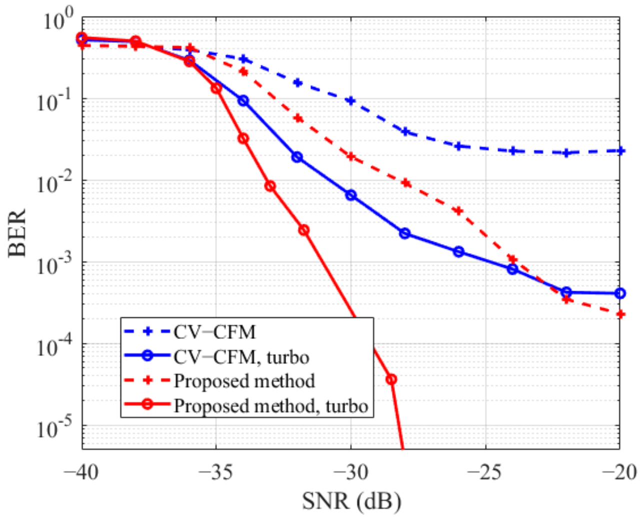

Figure 9. The UWA Channel simulation BER results.

In Figure 9, the BERs of the proposed method were similar to those in Figure 7 for AWGN. The conventional method in [12] showed an error floor at around a BER of 2×10^{-2}. The proposed method, however, achieved a BER of 10^{-3} at an SNR below -15 dB. The proposed method demonstrated a 7 dB SNR gain over the conventional method at a BER of 10^{-3}.

To verify the BER performance of the proposed method through practical ocean experiments, an experiment was conducted on 20 October 2019, in an area located 7 km away from the Shinjin-do coast in Taean, South Korea. The transmitter was deployed at a depth of five meters from the sea surface and used a Neptune-D17BB with a frequency range of 12.5 kHz to 19.5 kHz. The receiver with two TC4032 was deployed at depths of 5 m and 7 m with two channels each. The communication modulation parameters for the proposed and conventional methods were the same as those used in computational simulations, and the code length of L_c was set to three. The distance between the transmitter and the receiver was 1 km. Figure 10a–c provides the experiment location, experimental setup, and SSP.

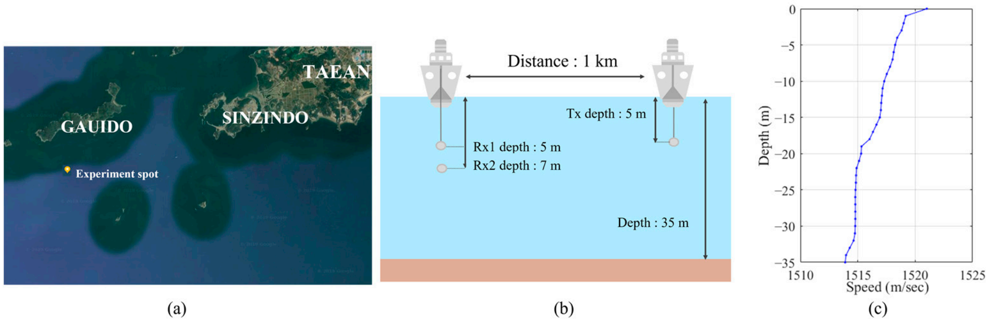

Figure 10. Ocean experiments environments (**a**) Location, (**b**) Configurations, (**c**) SSP.

Figure 11 represents a portion of the received signal using the proposed method. Both proposed and conventional methods transmitted whistles of 70 s and were repeated 100 times. The results of the ocean experiments are provided in Table 3.

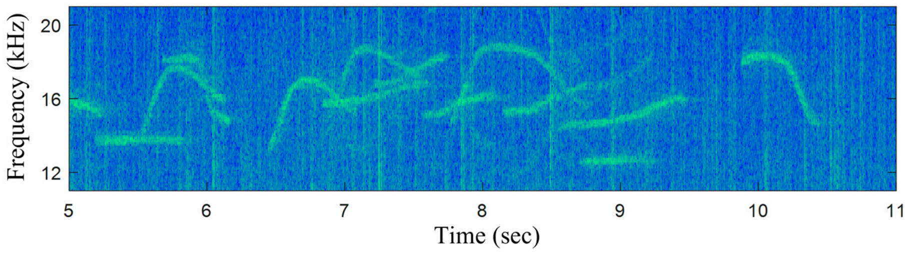

Figure 11. Ocean experiments received signals.

Table 3. Ocean experiment BER results.

Demodulation Scheme	BER (w.o. Turbo)	BER (w. Turbo)
Conv. method (Ref. [13])	0.13	6.3×10^{-2}
Proposed method	6.6×10^{-2}	1.3×10^{-4}

The received SNR of the ocean experiment data were estimated to be approximately −20 dB. In Figure 9, the BER with an SNR of −21 dB and turbo coding yielded around 10^{-4}, which is close to the results obtained from the ocean experiments. The maximum Doppler shift was estimated to be approximately 1.8 Hz. The proposed method consistently exhibited the lowest BER with a greater data rate in both the computational simulations and the real ocean experiments.

4.2. DoM Assessment for the Proposed Method

In this section, to demonstrate the superior similarity of the proposed method, an MOS test was performed by comparing the sounds of the proposed method with actual dolphin sounds. The MOS BS1284 standard provided by the International Telecommunication Union was used to evaluate the similarity between the mimicked whistles generated by the proposed method and the actual dolphin whistles. The MOS BS1284 is a standard used to evaluate the degree of distortion in speech communication and is adequate to evaluate the degree of similarity in the mimicked whistles [29]. The MOS score was assigned on a 5-point scale, and the number of participants needed to be greater than 20. The MOS test grading criteria are provided in Table 4.

Table 4. The MOS test grading criteria.

Score	5	4	3	2	1
Opinion	Same	Very similar	Similar	Slightly different	Different

In the MOS test evaluation, whistles generated by the proposed technique and real dolphin sounds were played to the participants in a random order for approximately 10 s. The whistles generated by the proposed technique were modulated by Table 1. Every mimicked whistle and real whistle were played three times per test, and 40 tests were conducted. The actual dolphin sounds used in the experiments were obtained from the "Watkins Mammal Database" [28]. Figure 12 shows a spectrogram of some of the audio files used in the MOS experiments. The experimental setup included the use of a Terratec A/D converter and AKG K52 headphones.

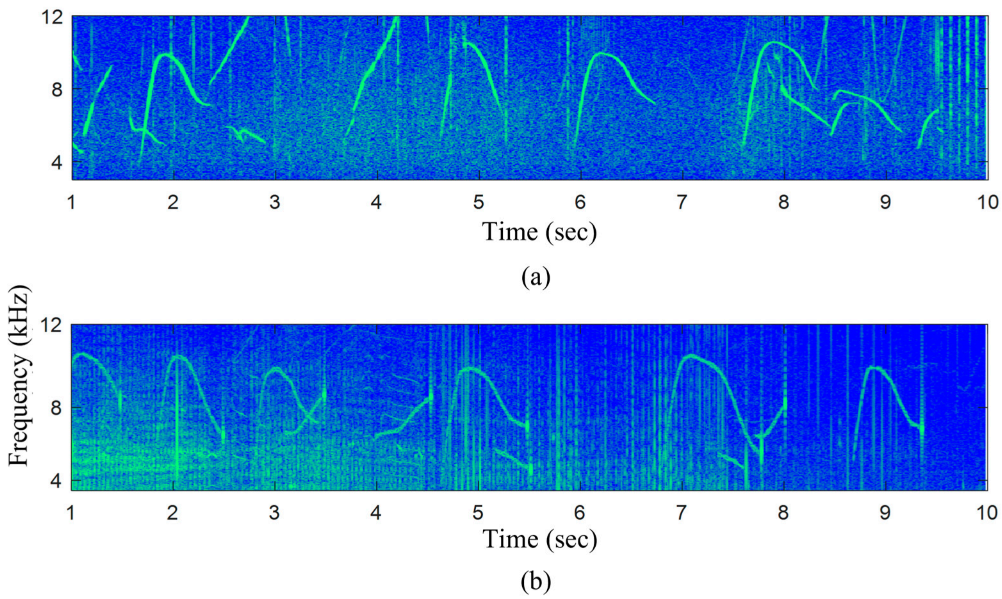

Figure 12. MOS test signal spectrogram, (**a**) real dolphin whistle, (**b**) proposed method.

A total of 32 participants participated in the experiment. Participants in the MOS test listened to two audio files and rated how similar they were to dolphin sounds using the MOS scale. The results of the experiment are summarized in Table 5.

Table 5. The MOS test results.

Scheme	Real dolphin	Proposed method
Score	3.72	3.67

The experimental results in Table 4 showed that only a 1.3% difference was measured between the real dolphin sounds and the sounds generated by the proposed method.

5. Conclusions

This paper proposes an underwater covert communications method with high covertness and a high data rate by mimicking a group of dolphin whistles. The modulation and demodulation of the proposed method were investigated using both TFSK and CV-CFM. Orthogonal codes were also used to mitigate the interference among multiple whistles. The data rate and BER performance of the proposed method were demonstrated and compared with those of the conventional methods through AWGN, a modeled underwater channel, and practical ocean experiments. In the modeled underwater channel, the proposed method achieved an SNR gain of 7 dB compared to the conventional method at a BER of 10^{-3}. In addition, the MOS test was conducted to measure the covertness of the proposed method. The MOS test confirmed a similarity of approximately 98.7% between the proposed whistle and the real dolphin whistle.

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References

1. Yang, T.C.; Yang, W.B. Low probability of detection underwater acoustic communications using direct-sequence spread spectrum. *J. Acoust. Soc. Am.* **2008**, *124*, 3632–3647. [CrossRef]
2. Ling, J.; He, H.; Li, J.; Roberts, W. Covert underwater acoustic communications. *J. Acoust. Soc. Am.* **2010**, *128*, 2898–2909. [CrossRef]
3. Shu, X.; Wang, J.; Wang, H.; Yang, X. Chaotic direct sequence spread spectrum for secure underwater acoustic communication. *J. Appl. Acoust.* **2016**, *104*, 57–66. [CrossRef]
4. Diamant, R.; Lampe, L. Low probability of detection for underwater acoustic communication: A Review. *IEEE Access Underw. Wirel. Commun. Netw.* **2018**, *104*, 19099–19112. [CrossRef]
5. Qu, F.; Qin, X.; Yang, L.; Yang, T.C. Spread-spectrum method using multiple sequences for underwater acoustic communications. *J. Ocean. Eng.* **2018**, *43*, 1215–1225. [CrossRef]
6. Schmidt, J.H. Using fast frequency hopping technique to improve reliability of underwater communication system. *J. Appl. Sci.* **2019**, *10*, 1172. [CrossRef]
7. Ko, S.J.; Kim, W.J. Robust frame synchronization algorithm in time varying underwater acoustic communication channel. *J. Acoust. Soc. Korea* **2020**, *39*, 8–15.
8. Song, L.; Gang, Q.; Asim, I. Covert underwater acoustic communication using dolphin sounds. *J. Acoust. Soc. Am.* **2013**, *133*, EL300–EL306.
9. Song, L.; Tianlong, M.; Gang, Q.; Lu, M.; Yanling, Y. Biologically inspired covert underwater acoustic communication by mimicking dolphin whistles. *Appl. Acoust.* **2017**, *120*, 120–128.
10. Ahn, J.M.; Lee, H.J.; Kim, Y.C.; Kim, W.J.; Chung, J.H. Multipath combining method for frequency shift keying underwater communications mimicking dolphin whistle. *J. Acoust. Soc.* **2017**, *17*, 404–411.
11. Ahn, J.M.; Lee, H.J.; Kim, Y.C.; Lee, S.K.; Chung, J.H. Machine Learning Based Dolphin Whistle Transceiver for Bio-Inspired Underwater Covert Communication. In Proceedings of the OCEANS 2019 MTS/IEEE SEATTLE, Seattle, WA, USA, 27–31 October 2019.
12. Ahn, J.M.; Lee, H.J.; Kim, Y.C.; Lee, S.K.; Chung, J.H. Mimicking dolphin whistles with continuously varying carrier frequency modulation for covert underwater acoustic communication. *Jpn. J. Appl. Phys.* **2019**, *58*, SGGF05. [CrossRef]
13. Lee, H.J.; Ahn, J.M.; Kim, Y.C.; Lee, S.K.; Chung, J.H. Time-frequency modulation based mimicking dolphin whistle for covert underwater acoustic communication. *Jpn. J. Appl. Phys.* **2020**, *59*, SKKF03. [CrossRef]
14. Gang, Q.; Tianlong, M.; Songzuo, L.; Muhammad, B. A frequency hopping pattern inspired bionic underwater acoustic communication. *Phys. Commun.* **2021**, *46*, 101288.
15. Lee, H.J.; Ahn, J.M.; Kim, Y.C.; Seol, S.H.; Kim, W.J.; Chung, J.H. OFDM based mimicking dolphin whistle for covert underwater communications. *J. Acoust. Soc. Korea* **2021**, *40*, 219–227.
16. Ahn, J.M.; Lee, H.J.; Kim, Y.C.; Kim, W.J.; Chung, J.H. Biomimicking covert communication by time-frequency shift modulation for increasing mimicking and BER performances. *Sensors* **2021**, *21*, 2184. [CrossRef] [PubMed]
17. Lee, H.J.; Kim, Y.C.; Seol, S.H.; Chung, J.H. Mimicking multiple whales whistles-based underwater covert communication. *IEEE Access* **2022**, *10*, 43934–43942. [CrossRef]
18. Gang, Q.; Muhammand, B.; Song, L.; Zeeshan, B.; Tianlong, M. Biologically inspired covert underwater acoustic communication-A review. *Phys. Commun.* **2018**, *30*, 107–114.
19. David, K.M.; Stephen, W.M.; Ronald, P.M.; Len, T.; James, J.Y. A method for detecting whistles, moans and other frequency contour sounds. *J. Acoust. Soc. Am.* **2011**, *129*, 4055–4061.
20. Douglas, G.; Marjolaine, C.; Jonathan, G.; Paul, W. Automatic detection and classification of odontocete whistles. *J. Acoust. Soc. Am.* **2013**, *134*, 2427–2437.

21. Tzu, H.L.; Lien, S.C.; Tomonario, A.; Hsiang, C.C. An automatic detection algorithm for extracting the representative frequency of cetacean tonal sounds. *J. Acoust. Soc. Am.* **2013**, *134*, 2477–2485.
22. Lior, S.; Carol, Y.; Robert, S.; Alexander, M.v.B.B.; Peter, T.; Filipa, S.; Patrick, M.; John, W. Classification of large acoustic datasets using machine learning and crowdsourcing: Application to whale calls. *J. Acoust. Soc. Am.* **2014**, *135*, 953–962.
23. Kim, Y.C.; Lee, H.J.; Ahn, J.M.; Chung, J.H. Selection of CDMA and OFDM using machine learning in underwater wireless networks. *ICT Express* **2019**, *5*, 215–218. [CrossRef]
24. Xuen, B.L. A high-rate orthogonal space-time block code. *IEEE Commun. Lett.* **2003**, *7*, 222–223.
25. Hsiao, H.C.; Shin, W.C.; Moshen, G. On next generation CDMA technologies: The REAL approach for perfect orthogonal code generation. *IEEE Trans. Veh.* **2008**, *57*, 2822–2833. [CrossRef]
26. Soo, C.P.; Shih, G.H. STFT with adaptive window width based on the chirp rate. *IEEE Trans. Signal Process.* **2012**, *60*, 4065–4080.
27. Kim, B.H.; Kong, S.H.; Kim, S.I. Low computational enhancement of STFT-based parameter estimation. *IEEE J. Sel. Top. Signal Process IEEE J-STSP.* **2015**, *9*, 1610–1619. [CrossRef]
28. Watkins Marine Mammal Sound Database. Available online: https://go.whoi.edu/marine-mammal-sounds (accessed on 14 September 2023).
29. Series, B.S. *General Methods for the Subjective Assessment of Sound Quality*; International Telecommunication Union: Geneva, Switzerland, 2003; Volume 1, pp. 2–16.