Camouflage Covert Communication in Air by Imitating Cricket's Sound

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ABSTRACT When the radio communication of an armed squad fighting in a jungle is interfered with by enemy's radio jamming equipment and their command and intelligence cannot be transmitted and exchanged, are there any other communication methods that can be used to solve such an emergency and covert communication problem? Focusing on this problem, a camouflage covert communication method (CCCM) in air is proposed by imitating cricket's sound. As well-known, there exist all kinds of animals' sounds in the jungle; however, hearing these animals' sounds, people generally considers them as background noise and ignores them. Based on this fact, the proposed CCCM uses the cricket's sound as the carrier wave, imitates the features of the cricket's call sequence to construct the camouflage communication sequence, and utilizes the time interval (TI) between two adjacent pulses to encode information. Meanwhile, other animals' sound is superimposed to the camouflage communication sequence to improve the camouflage ability of the generated communication sequence. Experimental results are provided to demonstrate the performance of the proposed CCCM.

INDEX TERMS Covert communication in air, bionic communication, animals' sound, cricket's call pulse.

I. INTRODUCTION

Wireless covert communication plays an important role in many fields, especially in military communications. Currently, radio waves are the most common choice for wireless communications, given their many advantages, such as long range and high speed etc.. However, with the development of radio interference technology, many advanced broadband and small-size radio jamming systems have been developed and they can effectively interfere with the radio communication process in broad frequency bandwidth for a certain purpose, which poses serious challenge to effective battlefield radio communication [1].

Consider one scenario, where an armed squad is fighting in a jungle, and the enemy uses a number of radio jamming devices to interfere with the communication process of the

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squad, resulting in that the military command and intelligence cannot be transmitted and exchanged among the squad members. Under such a dangerous situation, are there any other communication methods that can be used to solve this communication problem?

Taking this scenario as an example, in some emergency situations where radio communication is interfered or radio silence is required, a communication method that can replace radio communication is needed to transmit some brief and necessary command and intelligence among the squad members. It does not need a high communication rate but it needs to have strong camouflage ability so that it cannot be found by enemies.

As well-known, apart from radio waves, acoustic waves are also an effective carrier for information transmission. There have been many studies about acoustic wave based covert communication [2]–[5], and they can roughly be divided into two categories, depending on whether human beings can hear

the transmission or not. In the first category [2]–[4], the near ultrasonic frequency range (outside the human audible frequency range) is used. Since people cannot hear ultrasound, using ultrasound as a communication carrier has concealment ability. However, because the fading rate of acoustic waves increases with the increase of their frequency, the communication distance of such a covert acoustic system is rather limited and generally less than 20m, and these experiments were performed indoors. Different from the first category of studies, to achieve covert communication, in the second category [5], audible sound waves are used in some specific conditions and surroundings (e.g. the transmission of information is initiated at night after the staff leave the office). The application scenario is also indoor and the communication distance generally less than 10m.

More importantly, these researches mentioned above use artificial signals (such as continuous wave (CW), linear frequency modulation (LFM) etc.) as the communication carrier wave. Since these signals generally have distinct features [6], it is very easy for them to be detected and classified by enemy's reconnaissance system.

In addition, there are many researches [7]–[14] on biologically inspired covert communication in the field of underwater communication. For example, Liu *et al.* [8] used the original whistle and click of a dolphin as the communication synchronization code and information code, respectively. They modulated the communication information in the time difference between clicks, and constructed a disguised communication code sequence like a dolphin-like calling sequence. With a communication distance of 2 km, a communication rate of 37 bit/s and a communication BER of 10^{-4} were achieved in experiments on the lake. Liu *et al.* [9] also developed a covert communication method using high-energy whale sound to cover Direct Sequence Spread Spectrum (DSSS) signals from the perspective of energy masking. Through simulation, a communication BER of 2×10^{-4} is achieved under the condition of a communication distance of 40 km. Jia *et al.* [10] also proposed a bionic camouflage underwater acoustic communication method; this method uses the sea lion sound as carrier and the modulation is conducted on the main energy area of the click. Combined with the passive time reversal mirror technique, the feasibility of communication was verified in a 45 m pool. And in previous research [11], we have also proposed a method on bio-inspired steganography for secure underwater acoustic communications by constructing the communication trains using original whale call pulses.

Based on the above discussions, in this paper, a camouflage covert communication method (CCCM) in air is proposed by imitating the sound of some animals. As an example, again we consider the communication scenario for a jungle battlefield to show the principle of the proposed CCCM, although it is obviously not limited to this scenario. There exist all kinds of animal sounds in the jungle and generally, hearing these sounds, people regard them as surroundings noise and ignore them most of the time. Based on this observation,

the proposed CCCM uses animal sound as the communication carrier wave and simultaneously imitates the feature of the animal call sequence to construct the communication sequence. In this way, covert communication is achieved through the camouflaged sound.

To ensure good camouflage ability and feasibility of communication, the selected animals and their sound need to meet these requirements: 1) they are ubiquitous in the natural environment; 2) they are small and difficult to be found; 3) they have low frequency distribution for long range communication; 4) they have suitable features for communication encoding. After considering these factors, in this paper, we choose the cricket's call pulses sequence [15], [16] to serve as the target of imitation. Furthermore, the original call pulses are used as communication codes, and the time interval (TI) between two adjacent pulses is utilized to encode communication information. At the same time, other animals' sound is superimposed to the camouflage communication sequence to improve the camouflage ability of the communication sequence. The proposed CCCM has the following advantages:

(1) Since the original animals' call pulses are used as communication codes and the TI between two adjacent call pulses is imitated to encode communication information, the time-domain, frequency-domain, time-frequency and TI features of the original call pulse sequence are inherited and thus an attractive camouflage performance can be achieved.

(2) As the frequency distribution of selected animals' sound is lower than ultrasonic waves, a longer communication distance can be realized.

(3) The proposed CCCM can also be applied to other scenarios, such as intelligence covert exchange among spies, covert transmission of military airfield monitoring information etc.

II. CAMOUFLAGE COMMUNICATION ENCODING/ DECODING AND EXAMPLES

The key to the proposed CCCM is to keep the communication signal as close as possible to the animal's original call signal. In this section, we will first give an analysis about the features of the cricket's call pulses. Then we will introduce the principle and process of encoding method which can inherit these original features as much as possible. Then we will introduce the principle and process of decoding. Finally, we will summarize the methods we used to increase the camouflage ability.

A. FEATURES AND EXTRACTION OF THE CRICKET's CALL PLUSES

We performed a statistical analysis of the original high-quality call pulse sequence [17]. We found that these call pulse sequence is composed of many call pluses. The time-frequency spectrum (TFS) and waveform of the original sound of crickets are respectively shown in Figure 1(a)(b). And the TI between two adjacent call pulses is not fixed. Note that in this paper the TI is defined as the time difference
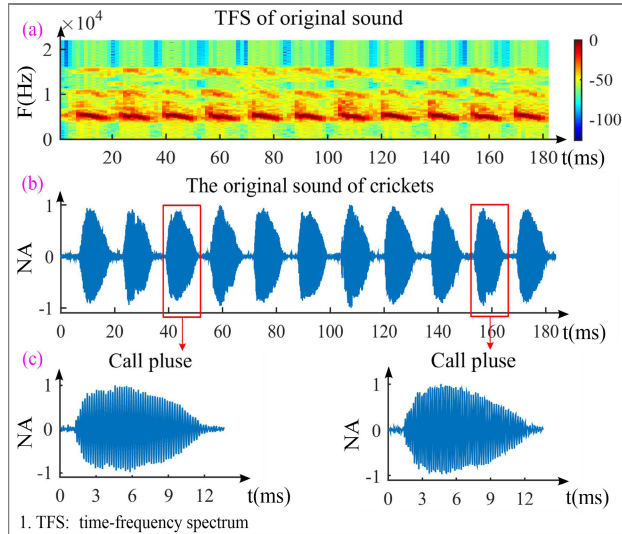
FIGURE 1. The features and extraction process of a segment of cricket's call pulse sequence.

between the end of the previous call pulse and the start of the next call pulse. And the characteristics of cricket's call pluses sequence are closely related to its species, behavior, time and surrounding, therefore it's extremely rich. More importantly, when multiple crickets call at the same time, the call pluses will overlap with each other, resulting in more diverse distribution of the TI between two adjacent call pulses.

Then, based on the short-term energy spectrum (STES) [18] of each call pulse, the call pulses is extracted to construct a call pulse database (CPD), which provides communication codes for subsequent camouflage covert communication encoding method. An example of two extracted call pulses is shown in Fig. 1(c).

B. CAMOUFLAGE COMMUNICATION ENCODING METHOD
Since the distribution of the TI between two adjacent call pulses in the true cricket's call pulse sequence is diversiform, and the characteristics of TI is difficult to be determined, we use the TI to encode the communication information. Generally, the communication frame is the most basic unit carrying communication information; therefore, the camouflage communication encoding method will be realized based on the communication frame. In the next, to ensure the effectiveness of communication and the camouflage ability of the communication pulses sequence, a novel communication frame is designed as shown in Fig.2 (a).

One communication frame consists of one synchronization code (SC) and multiple information codes (ICs). To make the effective communication pulse (ECP) sequence as similar as possible to the original call pulses sequence, each IC consists of a single original call pulse; to distinguish the SC from the IC, two adjacent call pulses with no TI are used to serve as one SC, which means that the SC has a wider pulse-width and higher energy than the IC. It is worth mentioning that

when multiple crickets call at the same time, there are two adjacent pulses with no TI in the true cricket's pulse sequence. The number (K) of ICs in one communication frame can be set according to the requirements of each application. In a communication frame, the SC is used as a timing reference (frame header) and $\tau_1, \tau_2, \cdots, \tau_K$ are the TIs between two adjacent call pulses (Fig. 2(a)). Assume that each TI can encode n bits of communication information. In detail, if τ_k satisfy:

$$m \cdot T_R < \tau_k < (m+1) \cdot T_R \quad (1)$$

where τ_k, k=1, 2, . . . , K is the k-th TI in a communication frame, T_R is the unit time, and the decimal value corresponding to the n bits communication information is equal to m, where m is a positive integer and m is smaller than 2^n. For example, if n is 2 and when m is 0 (corresponding to case 1 (#0) in Fig. 2(b)), the decimal value corresponding to the 2 bits communication information is equal to 0, and the corresponding information is '00'; when m is 3 (corresponding to case 4 (#3) in Fig. 2(b)), the decimal value corresponding to the 2 bits communication information is equal to 3, and the corresponding information is '11'. Generally, in order to maximize the detection tolerance during decoding, τ_k in the communication transmitter is set to satisfy:

$$\tau_k = m \cdot T_R + T_R/2 \quad (2)$$

And the mathematical expression of the encoded communication frame is:

$$s_j(t) = \begin{cases} P_S(t) & 0 < t < L_S \\ P_{Ii}(t - D_i) & D_i < t < D_i + L_{Ii} \\ 0 & \text{else} \end{cases} \quad (3)$$

where $s_j(t)$ is the j-th communication frame, $P_S(t)$ is the SC, $P_{Ig}(t)$ is the g-th IC, D_i is the offset of the i-th IC. The expression of D_i is:

$$D_i = L_S + \sum_{g=0}^{i-1} L_{Ig} + \sum_{g=0}^{i} \tau_g \quad (4)$$

where L_S is the pulse width of the SC, L_{Ig} is the pulse width of the g-th IC, τ_g is the width of the g-th TI.

In order to improve the camouflage ability of the constructed ECP sequence, we mix some other surrounding noises (OSNs) into the ECP sequence to further mimic the sound in the jungle. The OSN is determined according to the communication environment. Generally, other animal sounds in the environment are selected as the OSN. And the energy of the OSN is also determined based on the energy of other animal sounds in the actual environment. When the sounds of other animals in the actual environment are strong, the energy of the OSN can be reduced. When the sounds of other animals in the actual environment are weak, the energy of the OSN can be appropriately increased. When there are no other animal sounds in the actual environment, we can also not add OSN, of course, this situation is less likely to occur in the jungle.
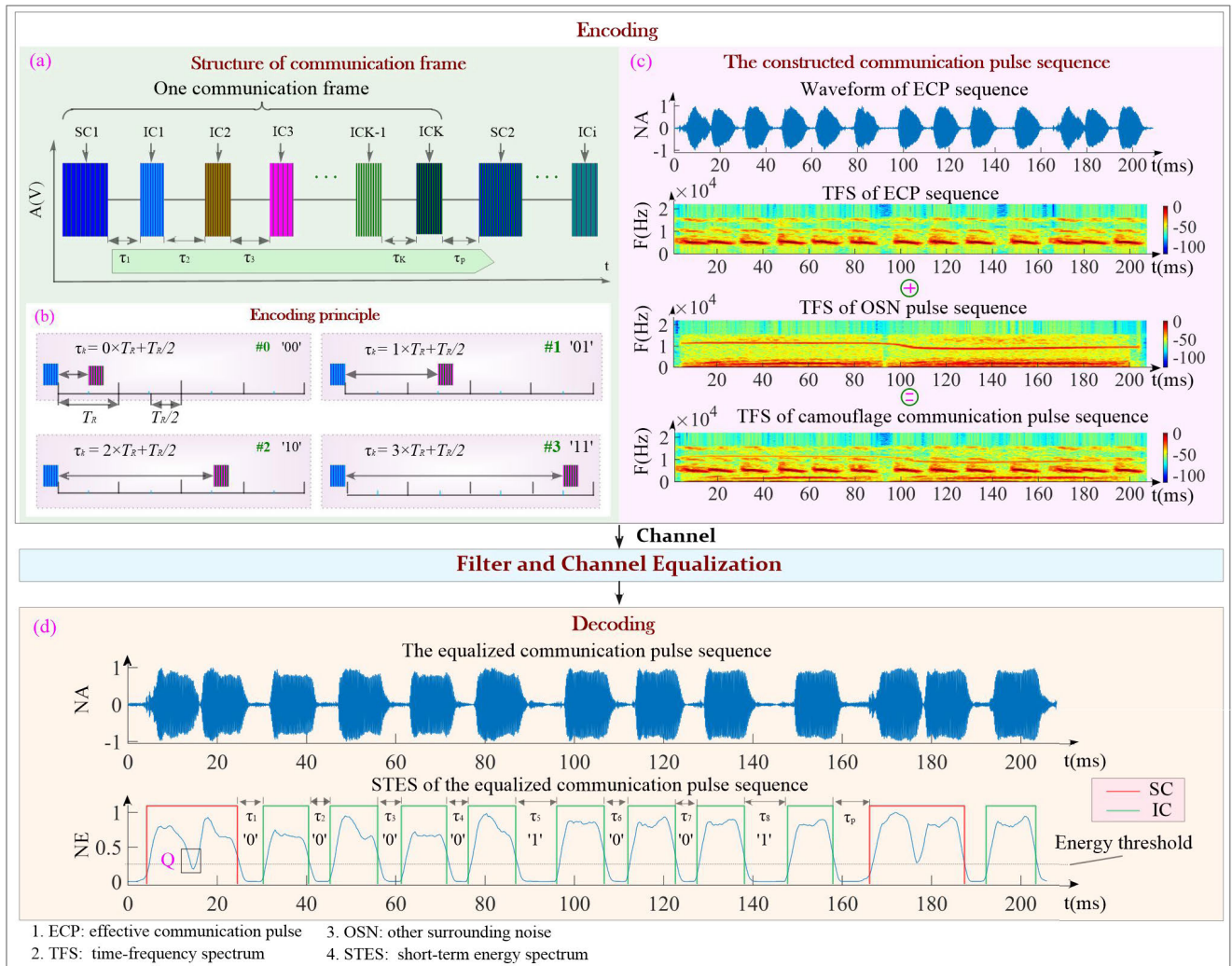
FIGURE 2. The camouflage communication encoding/decoding principles.

Please note that, in order to avoid affecting the ECP sequence and the decoding result and bit error rate (BER), the TFSs of OSN added into the ECP sequence are suggested not to overlap with the TFS of the ECP sequence, which is convenient for the communication receiver to filter out the OSN through a band-pass filter.

In order to explain the encoding method more clearly, we take a segment of communication signal from the experiment as an example. In this example, to match the feature of the true call sequence of crickets selected in this paper, T_R, n and K are set to 4ms, 1 and 8, respectively. The segment of communication signal is encoded based on the camouflage covert communication encoding principle described above and its waveform and TFS is given in Fig. 2(c). Bird call sequence whose TFS does not overlap with the TFS of the ECP sequence is used as OSN. The TFS of OSN pulse sequence and the TFS of the camouflage communication pulse sequence mixed with OSN is also shown in Fig. 2(c).

C. ENCODING PROCESS

Based on the above proposed encoding method, the entire encoding process can be summarized as follows.

S1: According to the features of the original call pulse sequence, set suitable T_R, n and K for high camouflage ability of the constructed communication frame.

S2: Group binary communication information to be encoded by taking n bits as a group. For example, assume that the binary communication information to be encoded is '10001101' and n is 2, the binary communication information '10001101' can be grouped into four groups, namely '10', '00', '11' and '01'.

S3: According to (2) $\tau_k = m \cdot T_R + T_R/2$, set the value of τ_k corresponding to each group of binary communication information.

S4: Generate one SC, and then generate K ICs in order according to the required TIs: $\tau_1, \tau_2, \cdots, \tau_K$. Before generating the next communication frame, keep one protection TI: τ_p between the last IC of

last communication frame and the SC of the next communication frame. Then, an ECP sequence is completed.

S5: Generate OSN pulse sequence, and then superimpose the OSN pulse sequence into the ECP sequence to generate the camouflage communication pulse sequence.

D. COMMUNICATION DECODING METHOD

At the receiver, the received communication pulses sequence is filtered by spectral subtraction filtering technology and one band-pass filter in order to remove the background noise and OSN, and then the ECP sequence is extracted. Next, the ECP sequence affected by the communication channel is equalized and compensated depending on the channel equalization method. Finally, the communication pulse sequence preprocessed by the filter and the channel equalization method is obtained and one part is shown in Fig. 2(d). To focus on the encoding and decoding process in this section, details of the band-pass filter and the channel equalization method are described in Section-III.

In the decoding process, to effectively distinguish the SC and the IC, and therefore correctly identify the TI between adjacent communication codes, the short-term energy spectrum (STES) of the communication pulses sequence is utilized. The STES of the communication pulses sequence is

$$E(m) = \sum_{n=mT}^{mT+N} \bar{x}(n)^2 \qquad (5)$$

where N is the window length and T is the frame shift, $\bar{x}(n)$ is the communication pulse sequence after filtering and equalization processing, $E(m)$ is the STES of the communication code sequence.

The STES of the communication pulse sequence corresponds to the "specific example" mentioned in Section II-B is calculated (N is set to be the time corresponding to 128 sampling periods, and T is set to be the time corresponding to 16 sampling periods, which is determined through multiple experiments) and one part is shown in Fig. 2(d). At different sampling rates, the values of N and T are different. And the values of N and T are usually small, in this way the STES can clearly represent the envelope of the communication pulses sequence. It can be seen clearly in Fig.2(d) that the SCs and ICs have higher energy than the TIs. It means that the communication codes (SC and IC) and the TI can be distinguished by the energy threshold (ET), the energy of communication codes is higher than ET and the energy of the TI is lower than ET. And the value of ET can be determined according to the STES of a specific communication pulses sequence transmit before formal communication. Meanwhile, the SC is wider than the IC, so SC and IC can be distinguished according to their duration.

It means that the SC and the IC, and then the TI can be located and distinguished accurately based on these differences. For example, the SCs are identified by the red rectangle and the ICs by the green rectangle in Fig. 2 (d).

Finally, the TIs: $\tau_1, \tau_2, \cdots, \tau_K$ can be calculated and the communication information is decoded exactly.

It is noteworthy that owing to relatively small energy at the connection point of two call pulses, there is a trough in the middle of the STES of the SC. Occasionally, this trough may be lower than ET (please see the Q point in Fig. 2(d)), and thus may result in that one SC is wrongly recognized as two ICs and one pseudo TI (PTI). To solve this problem, a decision strategy is designed. More specifically, according to the construction principle of the SC, the PTI is always far smaller than $T_R/2$, and thus we can utilize this condition to identify the SC correctly. As a result, when the PTI is smaller than $T_R/2$, the trough is ignored.

Based on the decoding principle proposed above, the entire decoding process can be described as follows.

S1: Filter out background noise and OSN by Spectral Subtraction and band-pass filter, and then equalize the extracted ECP sequence.

S2: Calculate the STES of the equalized ECP sequence.

S3: Locate the communication codes in the ECP sequence according to the principle that if the energy is higher than the ET in STES, the corresponding part of the signal is considered to be the communication pulse, and otherwise, it is considered as the TI.

S4: Distinguish the SC and the IC in the communication codes through the pulse-width differences between the SC and the IC (see Fig. 2(d)).

S5: Calculate the TI and decode the information according to the encoding principle. For the "specific example", the decoded information in Fig.2 (d) is '0 0 0 0 1 0 0 1'.

E. SUMMARY OF CAMOUFLAGE ABILITY

Based on the camouflage encoding principle designed above, we summary the camouflage ability of the communication pulses sequence from the following four aspects:

► Because the true call pulses of crickets are used as the communication codes, the time-domain waveform, frequency-domain distribution, time-frequency distribution of all camouflage communication codes are the same as those of the true call pulses of crickets, which means that the communication codes inherit all features of crickets' call pulses.

► Since the TI between the crickets' call pulses is not fixed and the distribution of the TI is diverse, with no obvious regularity. The TI between two adjacent communication pulses is used to encode communication information, which makes the communication pulses sequence very similar to the true call pulses sequence of crickets.

► Because the TI between two adjacent communication codes is calculated based on the STES, almost all call pulses can be used as communication codes since the STESs only depend on the short-term energy value and duration of call pulse. Therefore, the diversity of

communication codes can well inherit the diversity of the true call pulses of crickets.

► According the surrounding environment, appropriate OSNs whose TFS does not overlap with the TFS of the ECP sequence can be added into the ECP sequence to make the communication signal closer to the sound in the real environment, thereby further improving the camouflage ability of the ECP sequence.

III. CHANNEL EQUALIZATION

In order to effectively suppress the effect of channel on communication signals, a channel equalization approach based on the space diversity/combination [19] and Short-Time normalization (STN) technology are developed. In this section, we will introduce these anti-fading technology used in this paper.
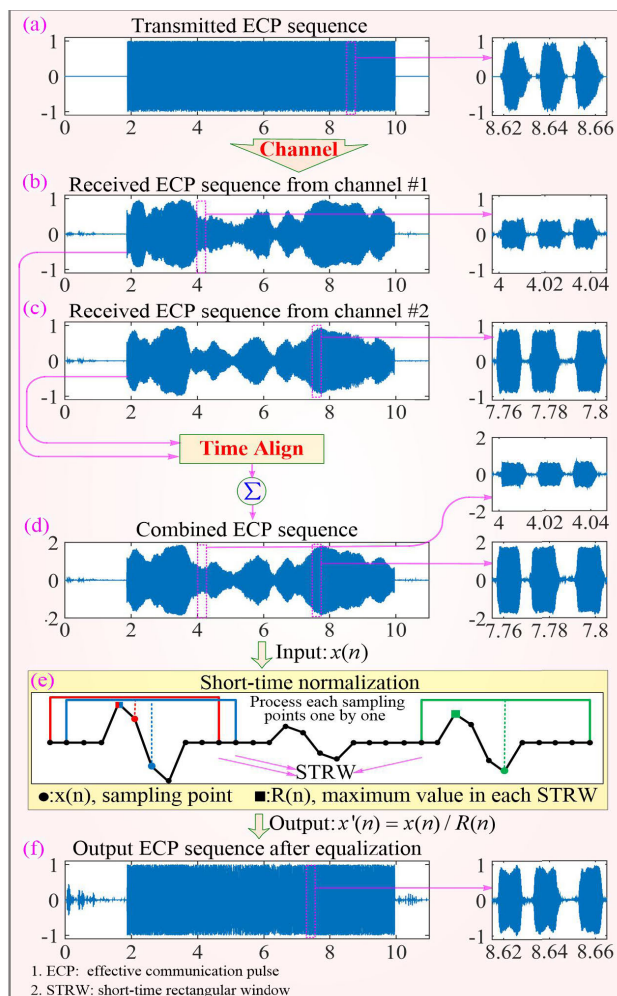

FIGURE 3. Principle and performance of channel equalization.

First, in order to achieve space diversity, multiple acoustic sensors are positioned with a distance among themselves. To ensure independent channels between the transmitter and different receiving acoustic sensors (see Fig. 3(b) and (c)), the distance is set to be larger than half wavelength of

the communication signals, which is easy to implement in practice.

Second, since these received communication pulses sequences from different acoustic sensors have different signal fading owing to multiple independent diversity channels, the fading probability of output signals is greatly reduced after these received ECP sequences are combined constructively. To have a low computational load and adequate performance, the Equal Gain Combining (EGC) approach [20], [21] is employed to combine the multichannel signals. It can been seen in Fig. 3(d) that the signal fading of the combined ECP sequence is greatly reduced and the signal to noise ratio (SNR) is significantly increased.

Although the SNR of the combined ECP sequence is greatly improved, its signal envelope amplitude is still fluctuant; as a result, the STES of communication codes with different signal envelope amplitudes will have large differences with each other. Under such conditions, if we use a constant ET to calculate the TI, it will lead to a large error. In order to solve this problem, a novel approach called Short-Time Normalization (STN) is developed. Considering that the fluctuation of the channel satisfies the short-term stationarity condition, in a short-time rectangular window (STRW), the envelope amplitude of communication pulses sequence is almost constant. Based on this, we can normalize the signal in a STRW, so that the envelope of the processed signal can be kept constant. To avoid signal phase transition between two adjacent communication codes, sliding STRW is adopted. That is, in each STRW, only the center sampling point is normalized, and then the STRW is shifted backward by one sampling period to normalize the next sampling point. And the STN approach has the following two steps:

1) Assume the combined ECP sequence contains Z sampling points, represented by $x(n)$, $n=1, 2, \cdots, Z$. Then, for each sampling point, a STRW which is represented by $w_n(m)$ with the width of $2q+1$ (q is a positive integer, so $2q+1$ is an odd) sampling periods is applied with the considered sampling point at the center of the window. In particular, the STRW corresponding to the first q sampling points is a rectangular window covering the first 2q sampling points, and similarly, the STRWs corresponding to the last q sampling points are a rectangular window covering the last 2q sampling points. More specifically, the expression for $w_n(m)$ is

$$\begin{cases} w_n(m) = \begin{cases} 1, & 0 < m < 2q \\ 0, & else \end{cases} & n < q \\ w_n(m) = \begin{cases} 1, & n - q < m < n + q \\ 0, & else \end{cases} & q < n < N-q \\ w_n(m) = \begin{cases} 1, & N - 2q < m < N \\ 0, & else \end{cases} & n > N-q \end{cases}$$

$$n = 1, 2, 3, \ldots N \quad (6)$$

where $w_n(m)$ is the STRW, q is a positive integer and $2q+1$ is the width of the STRW.
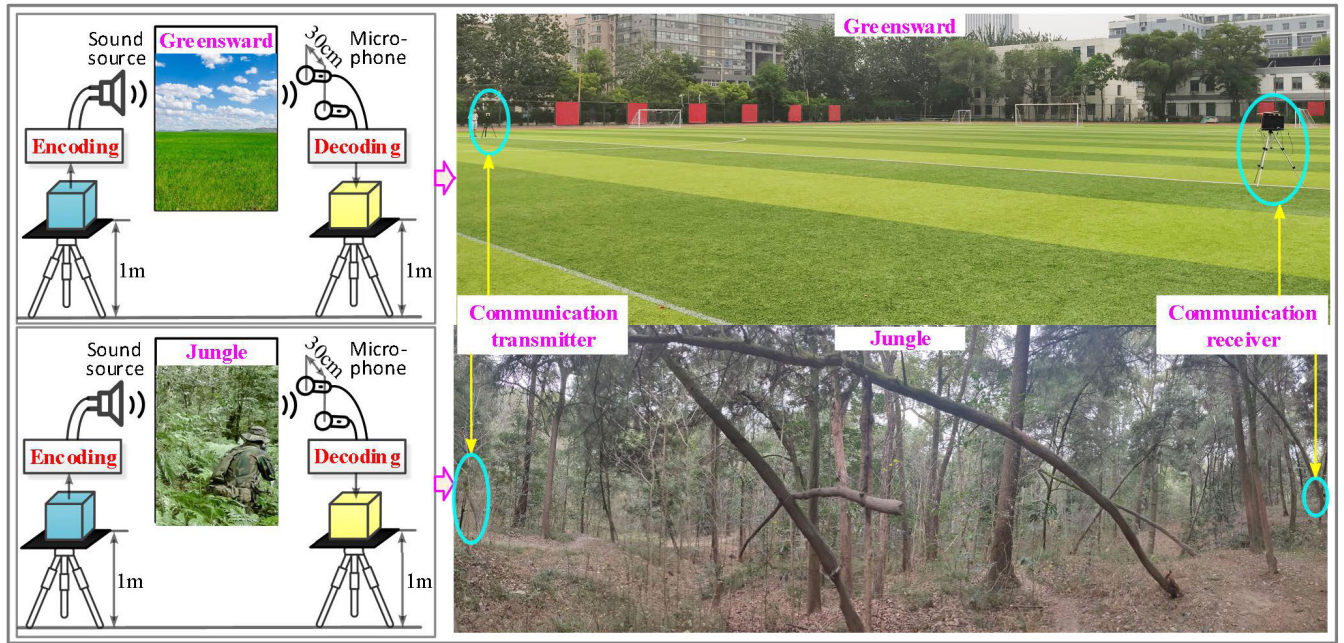
FIGURE 4. The experimental system.

2) $R(n)$ is the maximum value in each STRW and can be expressed as

$$R(n) = \max\{x(n) \times w_n(m)\} \qquad (7)$$

Then, normalizing each sampling point by $R(n)$ according to the formula:

$$\bar{x}(n) = x(n)\big/R(n) \qquad (8)$$

where $\bar{x}(n)$ is the normalized signal.

Fig. 3(e) shows the principle of the STN. Because there are too many sampling points in the real waveform, which cannot be clearly displayed, we use a schematic diagram to represent the communication pulse sequence. So that the relationship between the communication pulses and the sampling points and the STRW can be displayed more clearly. Each communication pulse is represented by 6 sampling points, and there are three communication pulses in Fig. 3(e). Since the pulses and the TIs need to be distinguished correctly through their energy difference during the decoding process, the relative amplitude characteristics of the pulses and TIs must be preserved during the STN. The STN is equivalent to using the relative amplitude to represent the signal in the STRW, so the STRW must contain one complete pulse and TI. In this way, the relative amplitude characteristics of a single pulse and TI are preserved.

Based on the above analysis, since the pulse-width of the communication pulse is set to 14ms, considering the maximal TI is equal to 6ms, the width of the STRW is set to the number of sampling points corresponding to 20ms in this paper.

IV. EXPERIMENT

Experiments are designed to verify the effectiveness and the camouflage ability of the proposed CCCM. In this section, we will introduce these experiments and the results obtained from these experiments.

A. FEASIBILITY OF COMMUNICATION

In order to examine the effectiveness of the proposed method, the greensward and the jungle were chosen as the experimental scenarios respectively and the experiment system is shown in Fig. 4. An Alpha 3-8 loudspeaker with a versatile operating bandwidth from 150Hz to 20kHz, was used as the acoustic source. A SPU0410LR5H-QB microphone with a usable frequency range from 100Hz to 80kHz, was adopted as the acoustic sensor. And the distance between the two receivers is 30 cm (approximately the width of the helmet). It is worth mentioning that in order to make the communication equipment concealed, the loudspeaker, microphones and other electronic components we choose have the characteristics of small size and low power. Based on the encoding process given in Section-II-C, the parameters n, T_R and k were set to 1, 4ms and 8, respectively. Because the length of TI between communication codes is used to carry communication bits, the communication data rate is not fixed, and the average communication data rate is about 46.9bit/s according to the encoding principle proposed in Section-II-B. It is worth noting that the communication data rate is directly related to the camouflage concealment performance. In this experiment, the appropriate n, T_R, and k were selected to make the constructed communication pulse sequence closest to the true cricket's call pulse sequence, which ensured strong
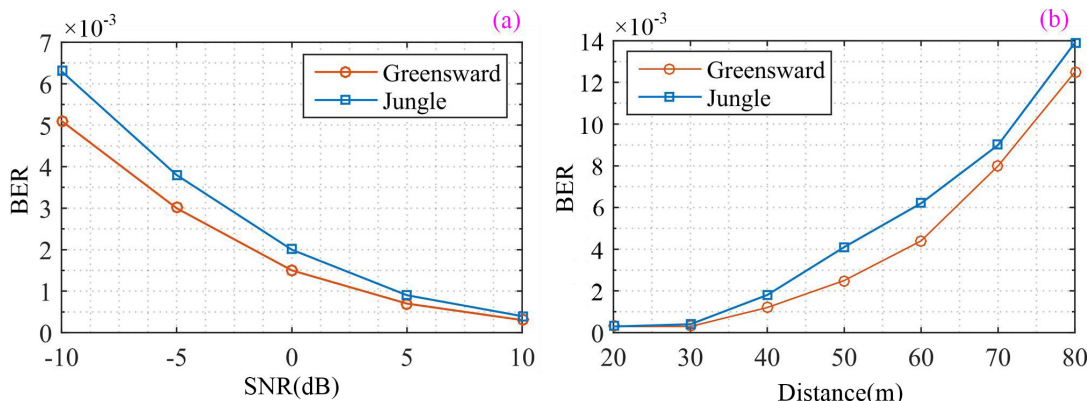
FIGURE 5. BER performance at different SNRs and communication distances.

camouflage concealment performance, but the communication data rate was limited.

In Section II we have demonstrated the feasibility of the encoding and decoding process with an example. Then we will measure the communication BER through two experiments to further verify the feasibility of this communication method. In the first experiment, the communication distance is set to 30m, and the communication BER is examined when the SNR in the communication receiver varies from −10dB to 10dB. It can be seen from Fig. 5(a) that the BER in the greensward is superior to one in the jungle, which is because that the acoustic channel in the jungle is more complex than the one in the greensward. Moreover, even if the SNR is as low as −10dB, the proposed CCCM can still achieve a BER of 6×10^{-3} and 5×10^{-3} in jungle and greensward, respectively. Meanwhile, with the increase of SNR, the BER decreases gradually, and the difference between the two scenarios gets smaller. When the SNR is higher than 5dB, the BER is better than 10^{-3}.

In the second experiment, the SNR is fixed to 5dB, and the BER is examined when the communication distance varies from 20m to 80m. As shown in Fig. 5(b), the BER in the greensward is lower than the one in the jungle. When the communication distance is 70m, the BER is still lower than 10-2, which is a very promising result for jungle communication.

It can be seen from the results of these two experiments that within 70m distance and under different SNR, communication experiments in the jungle and grassland have a low BER. It shows that the CCCM proposed in this paper has good effectiveness and can convey concise instructions in similar scenarios presented in the INTRODUCTION.

B. CAMOUFLAGE ABILITY OF COMMUNICATION

In the third experiment, we demonstrate the camouflage ability of the proposed CCCM from two aspects: human auditory perception and machine learning classification (see Fig. 6).

First, the human auditory perception is used through online survey. We produced twenty seconds long communication code sequence based on the proposed communication encoding principle and then a sample sound of the same
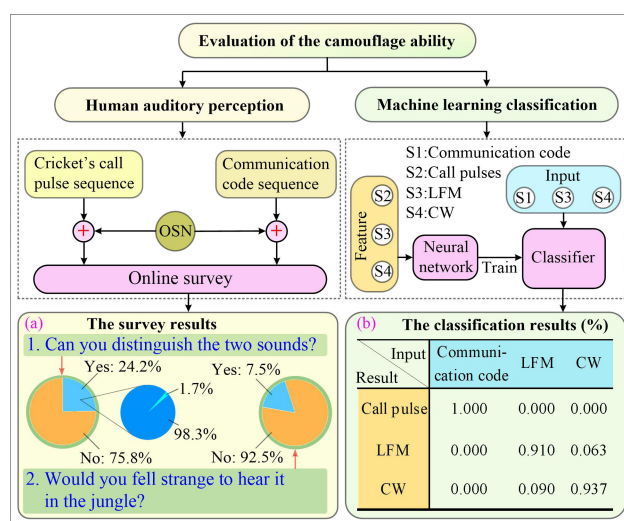

FIGURE 6. Test results for the camouflage ability.

length from the original cricket's call pulse sequence was taken. Then, through the form of a questionnaire survey, we send these two samples of sounds to our respondents, and invited them to listen to them and then answer the following two questions: 1) Can you distinguish these two sounds? 2) Would you feel strange to hear them in the jungle? A total of 240 respondents from different occupations (including veterans, professors, doctors and students) participated in this survey. The human auditory perception results are shown in Fig. 6(a). It can be seen that 75.8% of people cannot distinguish these two pieces of sounds; 24.2% of them can hear the difference between these two pieces of sounds; however, 98.3% of them pointed out that only the birds' sounds were different in the two pieces of sounds; in other words, 99.6% of people are unaware of the difference between ECP and true call pulse sequence of crickets in these two pieces of sounds. At the same time, 92.5% of people did not feel strange if they hear these two pieces of sounds in the jungle. The human auditory perception results demonstrate that the designed camouflage communication code sequence achieves a very attractive camouflage performance.

Second, machine learning classification is applied through the classical signal classification method (CSCM) based on the advanced neural network [22], [23]. Because there is no obvious regularity of the TI in cricket's call pulse sequences, and multiple crickets' sounds may be superimposed, this will make it more difficult to grasp the law of the TI in cricket's call pulse sequences. Therefore, here we only classify it with the traditional communication pulse based on the characteristics of the cricket's call pulse, regardless of the TI. Three kinds of signals, namely cricket's call pulses and conventional communication codes (CW pulses and LFM pulses) were recognized and classified by the CSCM. We first utilized the fifth-order polynomial $p(t)$ to fit the ridge of the TFS of the three kinds of pulses.

$$p(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 + e \quad (9)$$

And then the five coefficients a_0, a_1, a_2, a_3, a_4, a_5 and residual error e of the fifth-order polynomial were used as feature parameters to train the CSCM. Afterwards, 400 CW, 400 LFM and 400 cricket's call pulses were separately used to train the CSCM. Then, the trained CSCM was used to recognize and classify 300 communication codes, 300 CW pulses and 300 LFM pulses, respectively. It can be seen from Fig. 6(b) that the communication codes were classified as the cricket's call pulses with 100% probability, and the correct recognition rates of LFM and CW pulses were 91% and 93.7%, respectively. These classification results demonstrate that the designed communication codes have excellent camouflage ability.

V. DISCUSSION

Although we have realized communication using cricket's call pulses sequence as communication carriers, there are still many issues that need to be discussed.

Firstly, there are as many as 2500 types of crickets known all over the world, the features of call pulses sequence of each kind of cricket are different from each other, even for the same species of cricket, living in different regions. Therefore, it is extremely difficult to build a complete and standardized database of cricket's call pulse sequences for classification and recognition of cricket's call pulse sequences. So it is difficult to judge whether it is a true cricket's call pulse sequence or a communication pulses sequence when hearing the similar sound in the jungle. Not to mention that there are a mass of animal calls in the jungle, which are often ignored as background noise.

In addition, this communication method has some limitations. For example, when there are true cricket's sounds in the surrounding environment, we cannot use the cricket's call pulses sequence as the communication carrier, just like the channel conflict in the traditional communication method. Therefore, in subsequent research, we need to design more encoding and decoding methods that imitate the sound of other animals. In this way, in actual application, we can select suitable animal sound that does not exist provisionally in the current environment as the communication carrier.

And there are still some issues to be discussed in practical applications. In this article, we only realized point-to-point camouflaged covert communication to verify the feasibility and the camouflage ability of the communication method, but in actual application scenarios, communication between multiple nodes is required. Therefore, in subsequent research work, we also need to do more research on the camouflage covert communication between multiple nodes. To achieve camouflaged covert communication between multiple nodes, we also need to solve many problems, such as the identification of each node and interference between nodes, etc..

In addition, in practical applications, we may not know the position of other players, so we need to use the omnidirectional speaker to make the transmitter, so that we can ensure that the communication pulse sequence can be received no matter where the companion is. And there have been many studies on omnidirectional speaker technology [24]–[26]. And in the current experiment, the effect of multipath on the BER is slight, so we have not considered how to eliminate the effect of multipath. In subsequent studies, we will also conduct experiments in more severe environments. If multipath has a greater impact on the BER, we need to consider Time Reversing Mirror (TRM) or other techniques to eliminate the effect of multipath.

VI. CONCLUSION

It can be seen from the experiment results that the proposed CCCM in this paper can be used as an emergency communication method to transfer some concise and important information or commands when radio communication is interfered or radio silence is required.

Based on the camouflage strategy, the proposed CCCM in this paper uses the cricket's sound, which exists widely in the jungle, as the communication carrier wave, and imitates the TI features among cricket's call pulses to construct the camouflage communication pulses sequence. Compared with the conventional communication method based on conventional artificial ultrasonic waves, the proposed CCCM can simultaneously achieve stronger camouflage ability and longer communication distance. This communication method can meet the communication distance of 70 meters, and the BER is less than 10^{-2}. And when the communication distance is 30 meters, the BER is lower than 10^{-3}. In addition, the communication rate is about 46.9bit/s.

Moreover, the proposed CCCM is not limited to the jungle scenario and could also be applied to other similar areas requiring covert communication. For example, it can be used for underwater covert communication between submarines by imitating the sound of animals, covert communication between spies in the room and the outside world, and environmental-friendly underwater target detection.

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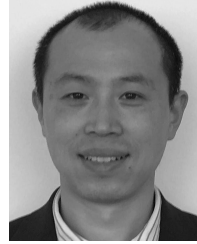
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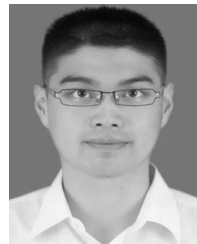
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