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A Basic Bio-Inspired Camouflage Communication Frame Design and Applications for Secure Underwater Communication Among Military Underwater Platforms

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ABSTRACT Many marine mammal species, such as different kinds of whales and dolphins, live together in groups. Although having no nice eyesight, they can accomplish cooperative foraging, inter-communication and group sailing very efficiently and accurately only depending on their sound. Generally, present interception systems almost always classify biological signals as ocean noise and try to filter them out. In addition, the covertness and security are very important for many military underwater platforms (MUPs) and their formations. Based on above classification fact and covert communication demand, this article designs a basic bio-inspired camouflage communication frame (BBICCF) for secure underwater communication among military underwater platforms based on the killer whale sound. According to characteristics of the killer whales' original call pulse trains, the original long duration call pulses (whistles and pulsed calls) are utilized as communication address codes for each MUP so as to provide disguised communication addressing support for interconnection among multiple MUPs in the same formation, and the original short duration call pulses (clicks) are used as other communication codes, so as to construct BBICCF for highly camouflaged conveying communication information. A simple and effective time-frequency (TF) contour extraction method is proposed to achieve the accurate extraction of the TF contour of the fundamental frequency of whistles and pulsed calls of killer whales for efficient classification and decoding of address codes. Next, this article provides some extensions and applications about how to let the BBICCF to be applied in conventional communication networks for MUP formation. Finally, simulation results show the effectiveness and concealment ability of designed BBICCF.

INDEX TERMS Secure communication network, underwater communications, whale sound, underwater formation.

I. INTRODUCTION

With the development of technology, more and more autonomous underwater vehicle (AUV), glider and varieties of formations composed of them are used in many military application scenarios from surveillance and anti-submarine, to reconnaissance and mine detection etc. [1]–[3]. Compared with single MUP, the formation composed of multiple MUPs can accomplish more complex, wider range, and more reliable military tasks [4], [5], just as multitudinous group animals in nature, such as whales, swarms, wolf packs etc.. However, the accomplishment of collaborative tasks among the MUPs, such as cooperative localization, sailing of multiple platforms, interaction of the order/data among multiple

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platforms etc., almost always depend on the *intercommunication line* among multiple platforms [6], [7].

The electromagnetic wave (e.g. light wave and magnetic induction wave) is an optional communication carrier in underwater. On the one hand, the underwater communication technology based on light waves can obtain high communication rate, however, the random channel of seawater greatly limits the communication distance [8]. Besides, how to achieve high-precision and fast light beam alignment at a long distance is a difficult problem for underwater optical communication, which greatly limits the practical use of underwater optical communication. On the other hand, the underwater communication technology based on magnetic induction principle requires large area induction coil and has very limited communication distance [9], which also greatly limits its application scenario. So far, the sound wave is the most effective information transmission carrier underwater, and thus is paid great attention in underwater communication. However, for transmitting acoustic wave outward in communication process, the platform is very easily found and then is recognized by the enemy's reconnaissance system [10]–[22]. Therefore, *the communication covertness and security are very crucial concerns for almost all MUPs and their formations*. How to establish a covert communication network [23] among MUPs in the same formation is the important research issue that is discussed in this paper.

From the perspective of the communication code waveform design, conventional covert communication methods can be divided as two categories [10]–[13], [18]–[22]. **In the first category**, those methods [10]–[13] try to gain the low probability of interception (LPI) by using the man-made communication signals (codes) with changed-parameters, such as frequency-hopping [10]–[12], time-hopping [13] and so on. However, the man-made communication signals (codes) have some distinct features. For example, although having changed-frequency, each frequency-hopping signal (code) generally consists of single continuous wave (CW) or linear frequency modulation (LFM) pulse. Unfortunately, the CW pulses have the distinct single-frequency feature in frequency-domain, and LFM pulses have the evident linear changed frequency feature [14] in frequency-domain, resulting in that these signals can be classified and identified [15]–[17] very easily. **In the second category**, those methods [18]–[22] try to gain the low probability of detection (LPD) by using low signal-to-noise-ratio (SNR) communication signals with LFM, FM-CW [18]–[20], or other stealth signals, such as pseudorandom [21] or chaotic codes [22]. Comparing with the first class of methods [10]–[13], the second class of methods obtain higher covertness because it is more difficult for low SNR communication signals to be detected by the enemy. However, the communication signals can still be detected by some methods, such as envelope detection [24], energy detection and energy spectral density analysis methods [25] etc. In addition, owing to low SNR of the communication signals, the communication distance is limited seriously, which is not beneficial for the long-distance communication.

Nature is Earth's most amazing invention machine for solving problems and adapting to significant environmental changes. Inspired by this, in 2001, a new underwater covert communication method is proposed in the annual technical report of the office of US naval research [26]. What impresses people is that it is not to hide the communication signals through LPI or LPD designs, but to hide the communication information by imitating or using the true marine mammal call pulses as communication codes. Whereafter, many related and in-depth technologies are studied in [27]–[30], and greatly promoted the development of bionic communication technology. However, these methods still have some limitations in terms of camouflage ability and application requirement. More specifically, [27]–[29] uses artificial LFMs to imitate the true clicks or whistles of dolphins, and utilize them to serve as camouflage communication codes. But, these signals are still artificial LFM signals, so there are still significant man-made features, which is very unfavorable for the covert ability. Gratifyingly, [30] provides a good method for constructing highly camouflaged communication signals, however, it only consider how use single whistle to carry communication information, but did not consider how to use all types of call pulses to construct camouflage communication sequence according to the permutation law of call trains of a certain whale. To sum up, the conventional methods considers more about using a certain type of call to construct a camouflage communication signal, while ignoring how to imitate the call train composed of all types of call pulses (such as whistle, pulsed call and click for killer whales) of a certain whale or dolphin. However, in the practical application, from the perspective of improving concealment, at least for a short period of time, the communication platform should emit call pulses of the same type of whale or dolphins according to the permutation law of the whale or dolphin call trains. At the same time, the conventional methods only studies how to imitate whale (or dolphin) calls to perform point-to-point covert communication, but never considers how to imitate whale (or dolphin) calls to construct highly camouflaged communication frames for communication concealment and addressing requirements of underwater communication networks.

As we know, killer whales are highly gregarious and usually consist of many individuals [31], so such a whale group can be considered as a nature whale formation. Owing to the dim light under seawater, their eyesight has deteriorated badly. Even so, they can accomplish cooperative group predation, intercommunication and cooperative group sailing very efficiently and accurately only depending on their calls. In fact, in shape, underwater platforms, such as AUV and glider, are very like killer whales. In addition, the interaction processes of the order/data among multiple platforms are very like the communication process among multiple killer whales. At the same time, according to [32]–[37], one can know that the present underwater reconnaissance systems with advanced underwater signal classification algorithms

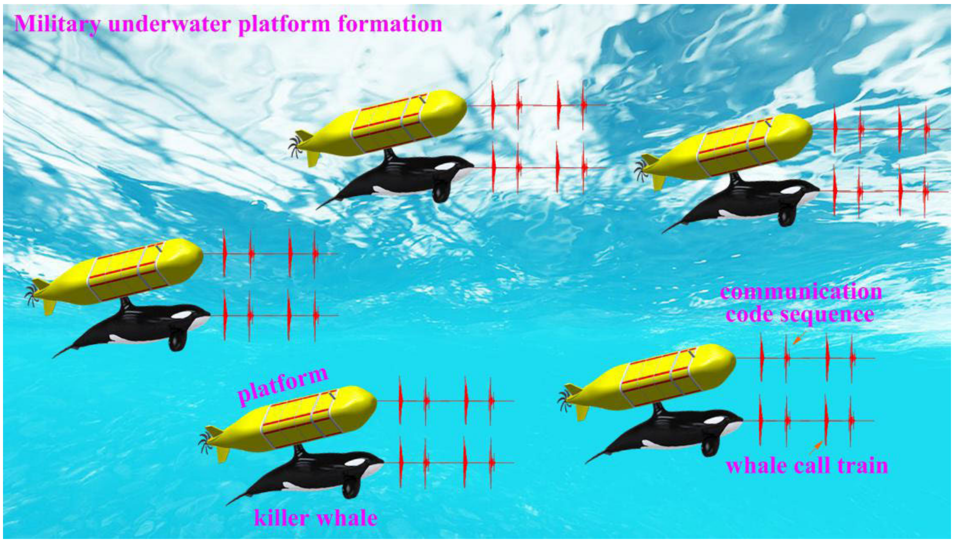

FIGURE 1. Camouflage communication strategy for MUP formations.

almost always classify the marine mammal sounds into ocean noise and try to filter them out.

Inspired by this, we design a BBICCF (Fig.1) to provide strong support for solving the secure communication and communication network problems for MUP formations, by using killer whales' call pulses and learning the bionic communication idea in [38], and then to extent its application for different formation requirements. The BBICCF considers each underwater platform as a killer whale, then picked out some original long duration call pulses (whistles and pulsed calls) with different features from the original killer whales' call pulse trains, and then allocates the selected unique long duration call pulse as communication **address code** for each platform. Next, the BBICCF uses the short duration call pulses (clicks) selected from the original killer whales' call pulse trains as **other communication codes**, and then simultaneously use both the time delay difference (TDD) among communication codes and the number of communication codes (NCC) to convey the communication information similar to the communication strategy in [38]. Then, fully imitating the characteristics of original killer whale call pulse trains, the BBICCF constructs a covert, disguised and trickish communication frame for the communication networks by utilizing the selected whistles, pulsed calls and clicks. Subsequently, from the perspective of communication frames serving the communication network, some extensive communication networks applications for some typical underwater platform formations are analyzed based on the designed basic bio-inspired camouflage communication frame.

The main contributions of this paper can be summarized as follows:

1) Different from the conventional point-to-point camouflage communication, we first propose a strategy of constructing a covert and small communication network by designing a basic bio-inspired camouflage communication frame according to the features and permutation laws of the calls of killer whales.
2) Make full use of different types, features and permutation law of the calls of killer whales, we propose to use whistles and pulsed calls to serve as the address codes for communication network, utilize the TF shapes of whistles and pulsed calls to distinguish different address codes, employ clicks of killer whales to serve as the information carrier, and use TDD among communication codes to form the communication sequence, which can highly match the features and permutation law of the calls of killer whales and thus obtain high camouflage ability.
3) A camouflage communication frame structure is design for small communication network according to the features and permutation law of the calls of killer whales.
4) A simple and effective TF contour extraction method is proposed. It only requires low computational cost and can achieve the accurate extraction of the TF contour of the fundamental frequency of whistles and pulsed calls of killer whales.

II. BIO-INSPIRED RELATIONSHIP WITH UNDERWATER PLATFORM FORMATION AND WHALE OR DOLPHIN GROUP

The whale order (Cetacea) is divided into several different families, one of them being Delphinidae (this includes all oceanic dolphin species). For example, killer whales are the largest member of this dolphin family, so they are both a whale and a dolphin at the same time. One of differences among them is that dolphins are generally smaller than whales.

Most of whales (contain killer whale) and dolphins are gregarious, highly social marine mammals. Each group of them consists of several or dozens of individuals [31]. Likewise,

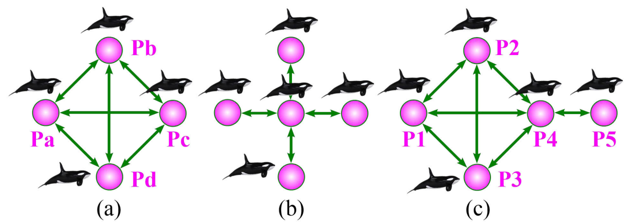

FIGURE 2. **The centralized, distributed and multi-hop communication networks.**

each underwater platform formation is composed of several or dozens of platforms. Therefore, from the perspective of structure and composition, the underwater platform formation is very like the whale or dolphin groups.

Second, whale or dolphin groups can produce multiple types of sounds, such as whistles, pulsed calls and clicks [39]. They rely on sound production and reception to travel cooperatively, communicate with each other, convey coordination of behavioral interactions between them and hunt cooperatively in dark or murky waters [40]. In other words, there exists a high-efficiency communication network inside the whale or dolphin groups depending on the sound wave. Likewise, in order to efficiently accomplish important military tasks, such as surveillance, anti-submarine, reconnaissance and mine detection, all individuals in each MUP formation must convey coordination of interactions between them, travel cooperatively, detect cooperatively, locate cooperatively, transmit order/data between each other, relying on the sound wave. Therefore, from the perspective of communication network, the underwater platform formation is very like whale or dolphin groups.

Third, through research and observation, researchers found that every individual in most of whale or dolphin groups can produce its own distinct stereotyped, individually specific signature whistle to realize distinction with other individuals [41]. And, researchers demonstrate that every individual in a bottlenose dolphin group can copy the other stereotyped whistles frequently and may use these stereotyped whistles to serve as descriptive labels in referential communication [42]. Likewise, for the communication frame of communication networks, it is an important basic that every individual in an MUP formation must has its own unique label, namely physical address. Therefore, from the basic of communication networks, the underwater platform formation is very like whale or dolphin groups.

In an underwater platform formation, the communication network architecture can typically be classified into three categories [43], [44], namely the *distributed (Fig.2(a)), centralized (Fig.2(b)) and multi-hop (Fig.2(c))* communication networks, as shown in Fig.4.

In the *distributed* communication network, all communication platforms are equivalent and thus can directly communicate with anyone other platform. Further, when needing to transmit information to another platform, a certain platform first can transmit the DA corresponding to the destination platform, then transmits itself SA, and finally transmits other communication information to the destination platform. In addition, when needing to broadcast information to all other platforms, a certain platform can use the *broadcast call pulses* to serve as its SA, and then transmit communication information to all other platforms. In the *distributed* communication network architecture, the route protocol is not required, but the collision avoidance mechanism is required when multiple platforms simultaneously transmit itself information to other platforms.

Similar to the *distributed* communication network, communication nodes, in the *centralized* communication network or in the multi-hop communication network, can communication with other each through those address codes.

In addition, in the centralized communication network architecture, the route protocol is also not required, but the collision avoidance mechanism is required when multiple followers simultaneously transmit itself information to the leader. In the multi-hop communication network, the route protocol is required. In the whole communication process, the communication address codes (namely various types of long duration call pulses) are used as the DA and SA, and are stored in the routing table of each platform.

III. BIO-INSPIRED SECURE COMMUNICATION NETWORK BASIS AND IDEAS

The underwater reconnaissance system is an important monitoring, surveillance and alarm tool, which is used to achieves the automated real-time detection and classification of biological (e.g. cetacean vocalizations) and anthropogenic acoustic signals (e.g. active sonar signals, communication signals, shipping noise, seismic surveys). For example, the advanced international project, LIDO (Listening to the Deep Ocean Environment [45]), can be used in real-time to trigger an alarm when cetaceans of interest or other potentially anthropogenic activities (e.g. military exercises, seismic surveys) is present at a given site by relying on the advanced detection and classification technologies. In addition, until now, we have searched and analyzed a good deal of relevant research achievements about the classification methods and strategies of underwater acoustic signals, and find that all classification methods and strategies integrated in enemy's underwater reconnaissance system almost always classifies these marine mammal sounds as ocean noise and then try to filter them out [32]–[37], just like the LIDO and ASPPS mentioned above.

Based the above facts, an interesting and under-investigated idea comes to our minds that if using the original biological acoustic signals (e.g. killer whale sound) to serve as communication codes, construct camouflage communication frame, transmit them according the characteristics of killer whales' call pulse trains, and establish communication network by imitating the social network of the killer whale group, we will probably be able to develop a covert communication information interaction method for MUP formations.

Next, let us analyze the characteristic of killer whales' call pulse trains before exploring the implementation procedure of our interesting and under-investigated idea.

IV. CHARACTERISTICS OF KILLER WHALES' CALL PULSE TRAINS

Killer whales echolocate by producing clicks, which are produced in series, quite variable in structure and have frequency peaks between 0.5 to 30 kHz [39], [40]. Click duration range from 0.1 to 20ms, and click repetition rates from **a few to over 300 per second** [39], [40]. There are abundant colorful and distinct whistles and pulsed calls in killer whales' call pulse trains. Whistles are characterized by a continuous waveform, which appears on a time-frequency (TF) spectrum as a call tone with little or no harmonic or side-band structure. The frequency of whistles ranges from about 1.5 to 18 kHz, with peak energy at 6 to 12 kHz [39], [40]. Whistle durations range from 50ms to 12s, and most contained a number of modulations or abrupt shifts in frequency. Pulsed calls are the most abundant and characteristic class of vocalizations produced by killer whales. Pulsed calls durations range from **50 ms to about 10 s** and their frequency ranges from 0.5 to 25 kHz, with peak energy at 1 to 6 kHz. The repetition rates of whistles and pulsed calls are from a few to more than ten [39], [40].

V. BBICCF DESIGN AND COMMUNICATION DECODING

Next, we design the BBICCF for MUP formations and then present its extensive applications.

A. TWO BASIC CONDITIONS OF ESTABLISHING A COMMUNICATION NETWORK

In order to establish a communication network, two basic conditions must be satisfied. First, the point-to-point communication link must be set up effectively. Then, every communication nodes must have a unique and distinct communication address (or called network address, Internet Protocol (IP) address) which is the key of communication addressing.

Meanwhile, it is well known that the characteristics of signal waveforms (namely acoustic wave in this article) in the physic layer is also key of achieving the covert, secure and disguised communication. Therefore, next, we will design the BBICCF based on these two basic conditions.

B. STRUCTURE DESIGN OF THE BBICCF

According to the characteristics of both the social network and call pulse trains of killer whales, a BBICCF is designed as Fig.3. It is composed of the destination address (DA), the source address (SA), the synchronization code (SC), the group-number indicator (GNI), the group-hopping indicator (GHI) and the information code (IC). Assume that there are L individuals in an underwater platform formation. In order to distinguish different individuals, $Q = L+P$ different long duration call pulses $w_1, \ldots, w_i, \ldots, w_L, \ldots w_Q$ with distinct features are screened out from original killer whales' call pulse trains. L of Q different long duration call pulses are used to serve as the communication address codes of L individuals. That is to say that each DA is composed of single long duration call pulse, is from L different long duration call pulses, and is used to identify the receiving platform. Likewise, each SA is composed of single long duration call pulse, is from L different long duration call pulses, and is used to identify the sending platform. P different long duration call pulses are designed to serve for specific network communication functions. For example, anyone long duration call pulse (e.g. the *th*-$(P+1)$ long duration call pulse) in the P different long duration call pulses can be used to indicate the broadcast task and this long duration call pulses is called as ***broadcast call pulses***. In other words, when the DA is the *th*-$(P+1)$ long duration call pulse, all platforms receive the communication information from the transmitting platform.

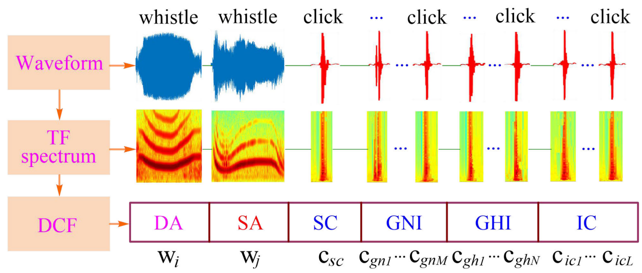

FIGURE 3. Structure of the designed BBICCF.

Besides, as [38], the SC is composed of single original click and used to serve as the time reference of decoding the GNI, GHI and IC. Communication codes $c_{sc}, c_{gn1}, \ldots, c_{gnM}, c_{gh1}, \ldots, c_{ghN}, c_{ic1}, \ldots, c_{icL}$ for SC, GNI, GHI and IC are original clicks of killer whales. The GNI is used to indicate the group number of clicks of the IC in a BBICCF, and the GHI is used to indicate the group-hopping rules of IC. For more detailed principle and description about SC, GNI, GHI and IC in a communication frame, please see Reference [38].

C. STRUCTURE OF THE BBICCF DESIGN OF DISGUISED POINT-TO-POINT COMMUNICATION

As Reference [38], we use the same principle to achieve the disguised point-to-point communication (please see Fig.3 and 4 in [38]). In each communication frame, both the TDD between communication codes and the NCC are simultaneously used to convey the information bits. Further, all communication codes used for SC, GNI, GHI and IC are original killer whale clicks. The SC has low cross-correlation with any other clicks of each communication frame so as to ensure high synchronization reliability. M (and N) clicks which are used for GNI (and GHI) (see Fig.3 in [38]), namely M(and N) communication codes, are different from both each other and any other communication codes in each communication frame. Meanwhile, each of M (and N) communication codes has high auto-correlation with itself and low cross-correlation with all other $M-1$ (and $N-1$) communication codes for convenient decoding of the receiver. Finally, all ICs are different from both each other and any other communication codes in each communication frame. Moreover, each one of the two call pulses in the same group has high auto-correlation with itself and low cross-correlation with another.

The original high quality sound of 88 minutes and 27 seconds, which was produced by multiple killer whales [46], was recorded with 44.1ksps sampling rate. According to the pick method (PM) method in [38], and when setting the NE threshold value E_t to 0.5, the width of rectangle window (used to pick out each click) to 22ms, M to 4 and N to 4, respectively, 53 groups of clicks were obtained and are able to be used to encode the communication information based on the same principle as [38].

D. SELECTION AND CLASSIFICATION OF DISTINCT COMMUNICATION ADDRESS CODES

Owing to the communication address code must be unique for each individual in the same underwater platform formation, next, we will select out the distinct communication address code for each individual.

Based on [39], [40], one can know that the TF shapes of whistles and pulsed calls of killer whales have variability in structure, therefore, we can utilize the polytropic TF shapes to distinguish different whistles and pulsed calls, and further provide distinct communication address code for each individual. In addition, considering that the fundamental frequency of the whistles and pulsed calls is often the strongest component of the signal during a block [47], and the TF shapes of the harmonic frequency is the same with the TF shapes of fundamental frequency, therefore, the TF shapes of fundamental frequency is used to distinguish different whistles and pulsed calls.

To obtain the TF shapes (namely TF contour) of the fundamental frequency, some algorithms [48], [49] had been developed. However, they often require high computational cost. For example, although the TF contour of the fundamental frequency in [48], [49] achieves a good contour extraction performance, it need first convert sound to image, denoising, and then go back to sound, which will result in a high computational load.

In this paper, order to extract the contour of the fundamental frequency, a simple and efficient algorithm is proposed by tracking spectral peaks over time. Next, we describe this algorithm.

First, we use endpoint detection method based on the short-time energy [50] used in the conventional speech signal processing to identify the start and end points of all whistles, pulsed calls and clicks,

$$E_n = \sum_{m=-\infty}^{+\infty} [x(m) \cdot \omega(n-m)]^2 \tag{1}$$

where $x(m)$ denotes the call train of killer whales, $\omega(n-m)$ denotes the window function.

Based on the endpoint detection method, all whistles, pulsed calls and clicks were picked out. Fig.4 shows an example of endpoint detection process. First, a piece of killer whale call train is shown in Fig.4(a), then its TF spectrums (Fig.4(a)) is given accordingly, next, the nomorlized short-time energy (NSE) spectrum is caculated and the screening windows are generated (Fig.4(c)), finally, the screening windows are used to pick the call pulses (Fig.4(d)).

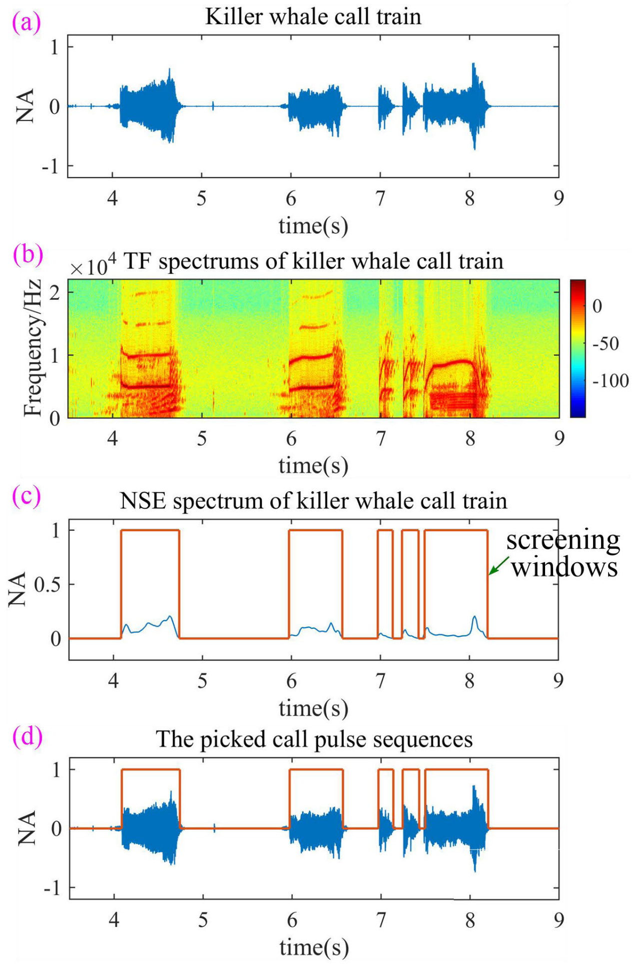

FIGURE 4. An example of endpoint detection process.

Second, to extract the contour of the fundamental frequency, the proposed simple and efficient algorithm is described in next section.

The short time Fourier transform, denoted by $X(t,f)$, where t is the time and f is the frequency, is computed using Hamming windows. Fig.5(a) shows a typical spectrogram form a portion of a killer whale whistle. The contour of the fundamental is clearly visible.

Next, we start to extract the contour of the fundamental frequency from $X(t,f)$. Assume the starting and ending time of a certain whistle or pulsed call are t_s and t_e, respectively. Then, we choose L time points uniformly between time interval $[t_s, t_e]$ and define them as $t_1, t_2, \cdots, t_l, \cdots, t_L$. In addition, assume there are H harmonics in each whistle or pulsed call.

Since the fundamental frequency of the whistles and pulsed calls has three independent features:

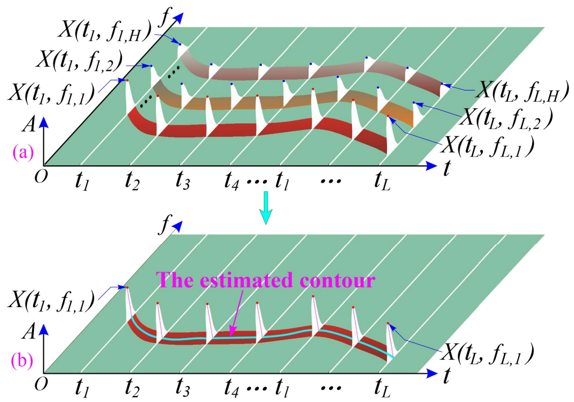

FIGURE 5. The extract process of the contour of the fundamental frequency. (a) a typical spectrogram form a portion of a killer whale whistle, (b) the contour of the fundamental frequency.

1) Compared to harmonics, the fundamental frequency has lowest frequency;

2) Compared to harmonics, the fundamental frequency is often the strongest component in the TF spectrum of the signal;

3) There is no frequency jump in the fundamental frequency of whistles or pulsed calls since the fundamental frequency is a continuous contour.

Based on the first two features, one can obtain the following results:

$$\begin{cases} Max[X(t_1,f)] = X(t_1,f_{1,1}) \\ Max[X(t_2,f)] = X(t_2,f_{2,1}) \\ \quad\cdots \\ Max[X(t_L,f)] = X(t_L,f_{L,1}) \end{cases} \quad (2)$$

where $Max[\cdot]$ is defined as calculating the maximum value.

Then, a vector $\mathbf{B}$

$$\mathbf{B} = [X(t_1,f_{1,1}), X(t_2,f_{2,1}), \cdots, X(t_L,f_{L,1})] \quad (3)$$

can be obtained.

Then, by sequentially connecting the values $X(t_1,f_{1,1})$, $X(t_2,f_{2,1}), \cdots, X(t_L,f_{L,1})$ in the vector $\mathbf{B}$, one can obtain the contour of the fundamental frequency, as shown in Fig.5(b).

However, in practical application, there may have some whistles or pulsed calls include segments where the magnitude of the harmonic exceeds the magnitude of the fundamental. At this time, if the contour is still extracted based on the principle in Equation (2), a wrong contour will be generated. Fig.6(a) gives an example. In this example, the vector $\mathbf{B}$ is

$$\mathbf{B} = [X(t_1,f_{1,1}), X(t_2,f_{2,1}), X(t_3,f_{3,2}), \cdots, X(t_L,f_{L,1})] \quad (4)$$

By sequentially connecting the values $X(t_1,f_{1,1})$, $X(t_2,f_{2,1}), X(t_3,f_{3,2}), \cdots, X(t_L,f_{L,1})$ in the vector $\mathbf{B}$, the contour is obtained (see Fig.6(b)). Obviously, this is an erroneous contour.

To avoid such problems, we propose a simple and effective contour extraction method.

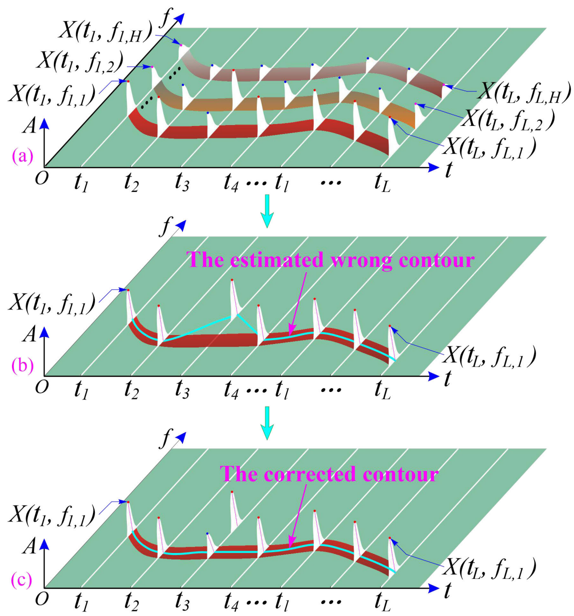

FIGURE 6. The principle of the proposed simple and effective contour extraction method.

First, based on the second feature, we can know that only a very small number of segments satisfy that the magnitude of the harmonic frequency exceeds the magnitude of the fundamental. For the convenience of description, we assume there is only one segment where the magnitude of the harmonic exceeds the magnitude of the fundamental, and in this segment, the maximum peak is $X(t_3,f_{3,2})$ as shown in Fig.6(b).

Then, based on the third feature of whistles and pulsed calls, one can obtain a fact that there is no frequency jump in the fundamental frequency of whistles or pulsed calls; therefore, the frequency satisfies the following relationship:

$$\begin{cases} |f_{l,1} - f_{l-1,1}| < f_{Th1} \\ |f_{l+1,1} - f_{l,1}| < f_{Th2} \end{cases} \quad (5)$$

where $f_{l,1}$ denotes the frequency value in the fundamental frequency contour corresponding to the time t_l, f_{Th1} and f_{Th2} denote two small frequency threshold value.

More specifically, for $l = 3$, we have

$$\begin{cases} |f_{3,1} - f_{2,1}| < f_{Th1} \\ |f_{4,1} - f_{3,1}| < f_{Th2} \end{cases} \quad (6)$$

when L is very large, the $f_{l.1}$ is close to $f_{l+1.1}$. Therefore, by setting the two threshold values f_{Th1} and f_{Th2} to two small numbers, one can obtain a simple judging condition. Obviously, according to this simple judging condition, we can judge that the maximum peak point $X(t_3,f_{3,2})$ is a wrong point because its corresponding frequency $f_{3,2}$ does not satisfy inequality (6). At this time, because $f_{3,1}$ satisfy inequality (6), we can replace $X(t_3,f_{3,2})$ with $X(t_3,f_{3,1})$, and then form a corrected vector $\bar{\mathbf{B}}$:

$$\bar{\mathbf{B}} = [X(t_1,f_{1,1}), X(t_2,f_{2,1}), X(t_3,f_{3,1}), \cdots, X(t_L,f_{L,1})] \quad (7)$$

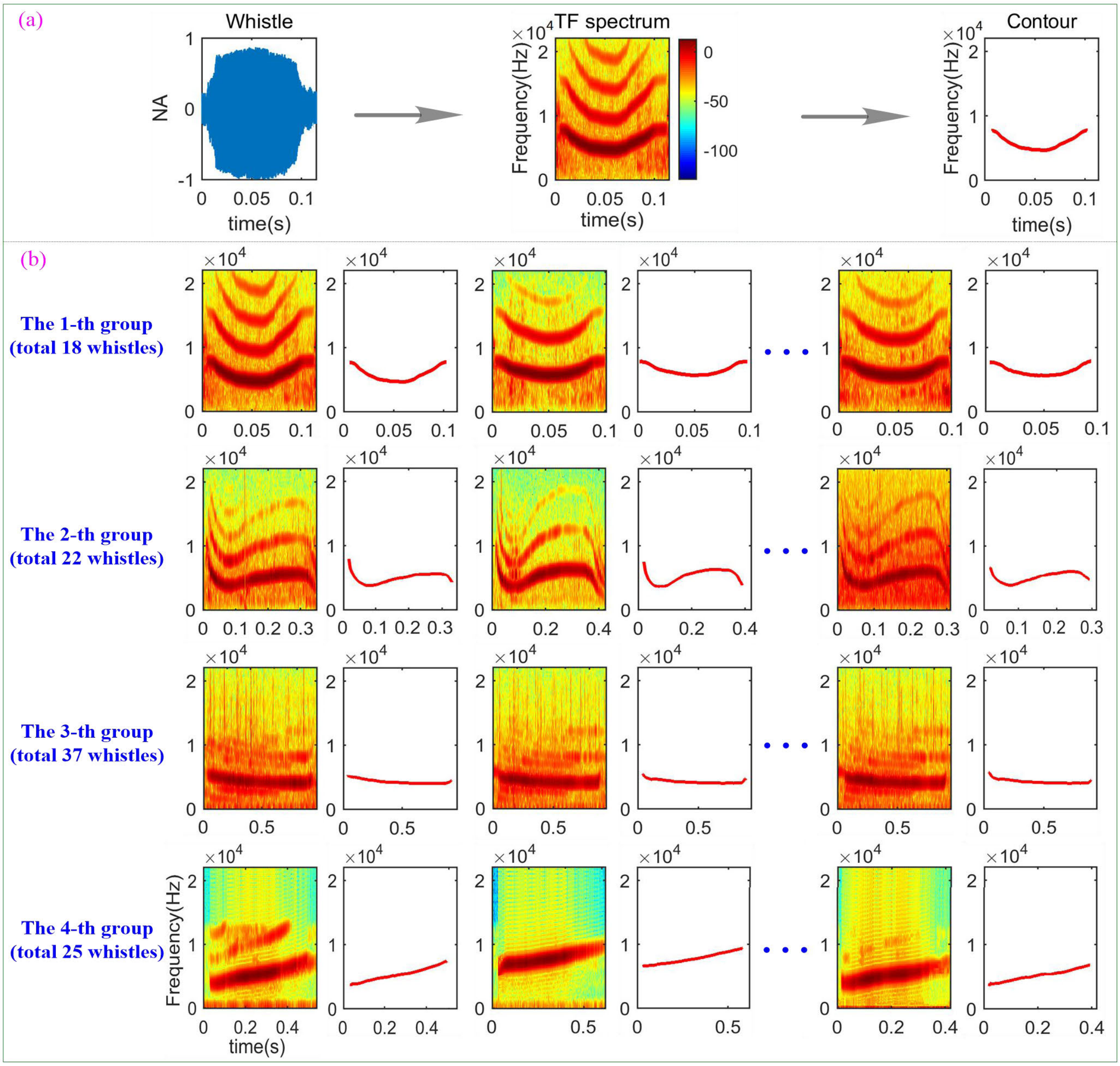

FIGURE 7. a) The extraction processes of TF contours of the whistles' maximum energy, b) 4 of 16 types of whistles' TF contours.

Then, by sequentially connecting the values in the vector $\bar{\mathbf{B}}$, the corrected contour of the fundamental frequency can be obtained as shown in Fig.6(c).

Further, when multiple consecutive points are not on contour of the fundamental frequency, the wrong points can also be corrected based on the proposed simple and effective contour extraction method.

Based on the proposed improve method mentioned above, the extracted contour of fundamental frequency is shown in Fig.7(a).

Based on the proposed simple and effective time-frequency (TF) contour extraction method, after the killer whale's sounds of 88 minutes and 27 seconds are processed, 286 whistles and their TF contours are obtained. Then, by borrowing the McCowan method [51]–[52] to classify 286 TF contours of whistles and pulsed calls, we obtain $Q = 16$ types of TF contours of whistles and pulsed calls.

Limited by the page size, we only show 4 of 16 types of TF contours of whistles and pulsed calls in Fig.7(b).There were 18, 22, 37 and 25 long duration call pulses in the 1-th, 2-th, 3-th and 4-th groups.

Next, we choose the l-th type of long duration call pulses corresponding to the l-th type of TF contours of long duration call pulses to serve as communication address code of the l-th platform, and the rest P types of long duration call pulses corresponding to the rest P types of TF contours of long duration call pulses are used to serve as achieve specific network communication functions.

It is worth mentioning that there are multiple long duration call pulses corresponding to each type of TF contours. If we only choose one specific long duration call pulse from multiple long duration call pulses to serve as communication address code for one platform, the long duration call pulse will be single rather than diverse, which may result in some

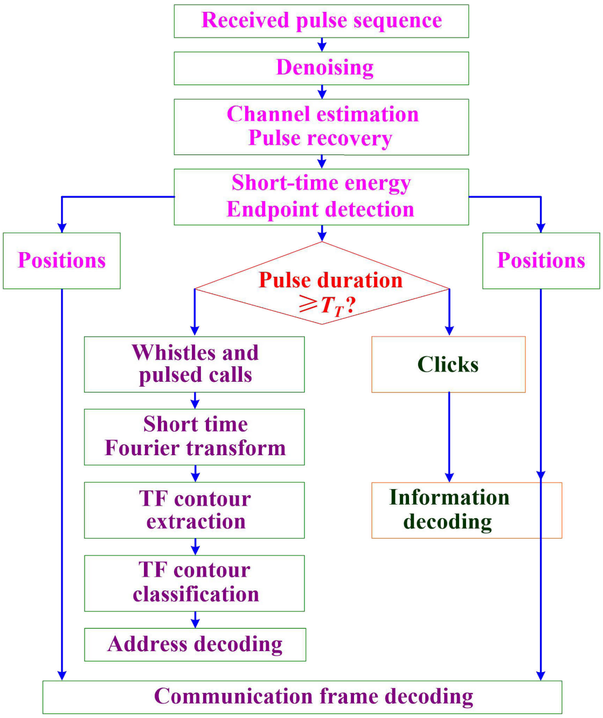

FIGURE 8. The process of decoding of communication.

recognizable features which may be identified by the enemy's underwater reconnaissance system. So, we can use anyone of the multiple long duration call pulses corresponding to each type of TF contours of long duration call pulses rather than one specific long duration call pulse to as communication code when transmitting the communication frame every time. In addition, the pulsed calls can be inserted in the time interval between two adjacent communication frames to improve the camouflage ability of the communication frame sequence, or can also be used to carry communication information through some encoding and decoding approaches to be developed in the future research work.

E. DECODING OF COMMUNICATION

The process of decoding of communication can be described through Fig.8.

First, the spectral subtraction [53] is used to remove the additive noise and then the wavelet denoising technology [54] is utilized to remove the high-frequency noise mixed in the received pulse sequence. Second, the passive time reversal mirror (PTRM) approach [55] is used to estimate the channel and recover the communication pulses. More specifically, multiple hydrophones (means multiple signal acquisition channels) are installed along the MUP's side to receive the communication; the call pulse with sharp auto-correlation is used to serve as the channel probe signal. Next, compute the pulse duration and identify the position of each pulse in the communication code sequence.

Third, the pulse duration is judged. Further, if the pulse duration is less than T_T, the pulse is classified into click; otherwise, the pulse is classified into whistles or pulsed calls, where T_T is a time length threshold. Next, the decoding of short duration call pulses (clicks) corresponding to the encoding in Section-V-C can be achieved based on the position of each click in the communication code sequence and the cross-correlation method proposed in [38].

Then, obtain the TF spectrum of each whistle or pulsed call through the short time Fourier transform. Next, extract the TF contour of fundamental frequency of each whistle or pulsed call by using the proposed simple and effective time-frequency (TF) contour extraction method.

Then, based on the McCowan method [51]–[52] again, decode the contours of the fundamental frequency of whistles or pulsed calls and classify each contour into one of $Q = 16$ **types** of TF contours of whistles and pulsed calls. That is to say, that one can identify which type each contour of the fundamental frequency of each whistle or pulsed call belong to, and then the decoding process of each received whistles or pulsed calls is accomplished.

Finally, according to the decoding results of clicks and whistles or pulsed calls and their positions in the communication code sequence, the decoding process of each communication frame is achieved.

VI. EVALUATION

Four simulations are executed to evaluate the validity and camouflage ability of communication.

Considering that the encoding and decoding of a variety of communication frames (which contain clicks, whistles and pulsed calls) among different platforms are keys of affecting the communication quality, so, in the first simulation, the communication network architecture in Fig.2(a) is used since it contains all information interaction links in the network communication process. Please note that since the communication frame is the basic unit and basis of information interaction in communication networks, so this paper focuses on the design of camouflage communication frames and do not discuss the network protocol. In the simulation, assume that the communication process are performed according to the following order: Pa→Pb, Pa→Pc, Pa→Pd, Pb→Pc, Pb→Pd, Pc→Pd in Fig.2(a). The first four types of 16 types of long duration call pulses (see Fig.7) are assigned to Pa, Pb, Pc and Pd in sequence, and the fifth types of 16 types of long duration call pulses are assigned to serve as the *broadcast call pulses*.

Assume that the underwater platforms in the same formation are sailing in a small area of the sea; for example, according to the distributed shape in Fig.7(b), the distances between Pa→Pb, Pa→Pd, Pb→Pc, Pc→Pd, Pa→Pc, Pb→Pd are set to 200m, 100m, 400m, 300m, 384m, 250m, respectively. All TDDs between two adjacent ICs are set to be more than 30ms and less than 500ms, the TDD between the DA and the SA is set to be 500ms, and the TDD between the SA and the SC is set to be 400ms, which is consistent with the repetition rates of clicks, whistles and pulsed calls of killer whale. Please note that, according to different application requirements, the TDD between between IC and IC can be

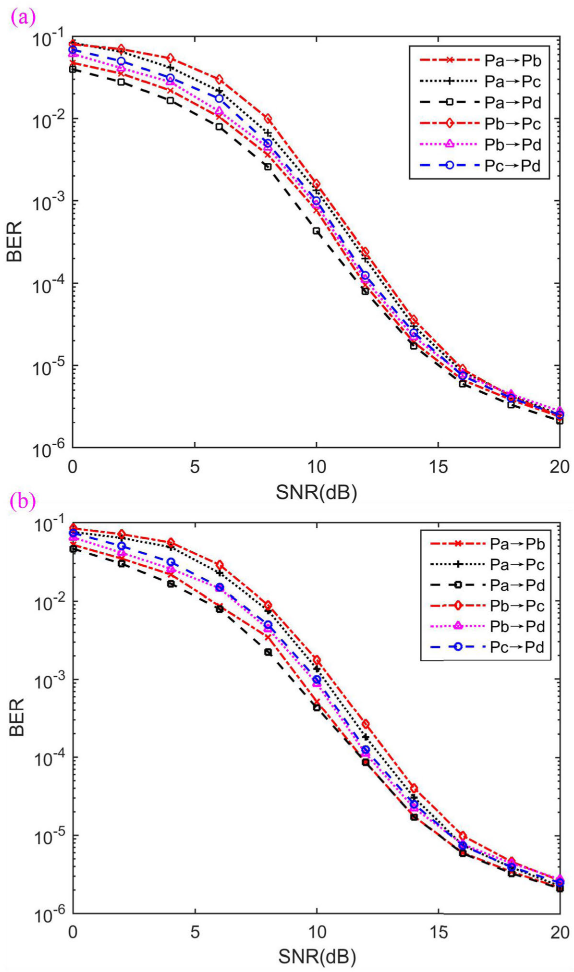

FIGURE 9. The comparison with the proposed bio-inspired camouflage communication method and the conventional TDD communication method. (a) The communication BER among all platforms in the same formation based on the proposed bio-inspired camouflage communication method, (b) The communication BER among all platforms in the same formation based on the conventional TDD communication method.

set in interval (3ms,500ms), TDDs between DA and SA can be set in interval (50ms,12000ms), and the TDD between SA and SC can be set in interval (50ms,10000ms). BELLHOP [56], [57], which is an efficient and widely used toolbox and is a beam tracing model for predicting acoustic pressure fields in ocean environments, is used to imitate the underwater acoustic channel. Further, for the environmental parameters, seawater density was set to 1.026g/cm^3, seafloor density, that was supposed to be sandy, was 1.938g/cm^3, sound speed in the bottom was 1700m/s and the mean seawater sound speed was 1500m/s.

The passive time reversal mirror (PTRM) approach [55] is used to estimate the channel and recover the communication pulses. The bit error rate (BER) results of communication are shown in Fig.9(a). It can be seen that as the SNR increases, the BER drop quickly, and when the SNR is higher than 15dB, the BER is better than 10^{-5}. Considering that the proposed method has similar communication modulation principle with the conventional TDD communication method [58], the conventional TDD communication method is simulated for comparison; in this simulation, four LFM pulses with different slope of change (0.5, 1, -1, -0.5) in frequency were used to serve as the SA for Pa, Pb, Pc and Pd, respectively. Another LFM pulse with slope of change (1.5) in frequency was used to serve as the IC. Other simulation conditions are the same with the proposed bio-inspired camouflage communication method. Fig.9(b) shows the simulation results. Comparing Fig.9(a) and (b), one can see that the proposed bio-inspired camouflage communication method obtain very close communication BER performance with the conventional TDD communication method.

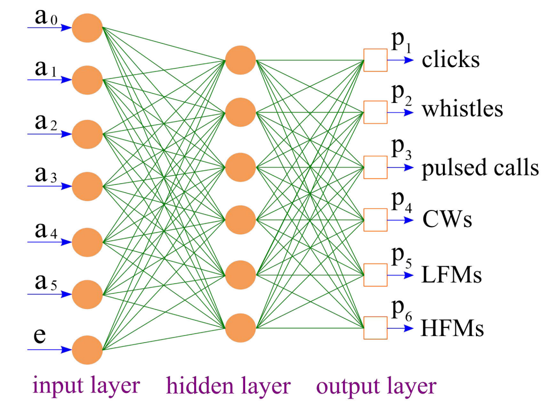

FIGURE 10. The structure of the used neural network.

In the second simulation, the camouflage ability of communication codes is examined by the signal classification method in [59]. Similar to [38], a five order polynomial $p(t)$ is used to fit the TF contour of each pulse (click, whistle, pulsed call, CW, LFM, HFM),

$$p(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 + e \quad (8)$$

and then five coefficients $a_0, a_1, a_2, a_3, a_4, a_5$ and residual error e of the five order polynomials were used to train the neural network, shown as Fig.10. Log-Sigmoid function is used between input layer and hidden layer, between hidden layer and output layer. Tan-Sigmoid function is used between output layer and output result. Tan-Sigmoid function can limit the output value in interval (0,1), and each output value reflect the degree of confidence that the current features can be classified into a certain signal type. In addition, the threshold value of the residual error is set to 0.001, and the maximum number of iterations is set to 3000. Afterwards, 100 CWs, 100 LFMs, 100 HFMs, 100 clicks, 100 whistles and 100 pulsed calls were separately used to train the neural network, and then the trained neural network is utilized to classify and recognize 200 CWs, 200 LFMs, 200 HFMs, 200 clicks, 200 whistles and 200 pulsed calls, respectively. The classification results were shown in Table.1.

To ensure and enhance the camouflage ability of communication frame, we have taken three measures. **First**, we use the original killer whale clicks, whistles and pulsed calls to serve as communication codes, which can let the communication codes fully inherit the waveform, frequency distribution

TABLE 1. The classification results.

True signal types	The ratio of classified such type of signal						The average classification accuracy rate
	Click	Whistle	Pulsed call	CW	LFM	HFM	
Click	0.9282	0.0136	0.0157	0.0198	0.0123	0.0104	0.9282
Whistle	0.0133	0.9321	0.0115	0.0182	0.0097	0.0152	0.9321
Pulsed call	0.0128	0.0139	0.9385	0.0132	0.0106	0.0110	0.9385
CW	0.0262	0.0092	0.0077	0.9223	0.0147	0.0199	0.9223
LFM	0.0192	0. 0296	0.0131	0. 0215	0.9379	0.0298	0.9378
HFM	0.0085	0.0102	0.0092	0.0101	0.0144	0.9476	0.9476

TABLE 2. The comparison of TDD between the true call pulses and communication codes.

Types	Range (ms)	Types	Range (ms)
TDD between clicks	(3,500)[39-40]	TDD between IC and IC	(3,500)
TDD between whistles	(50,12000)[39-40]	TDD between DA and SA	(50,12000)
TDD between pulsed calls	(50,10000)[39-40]	TDD between SA and SC	(50,10000)

and TF distribution features of original killer whale sounds, and thus achieve the camouflage of communication codes. **Second**, we construct the communication frame according to the repetition rate characteristic of clicks, whistles and pulsed calls of killer whales, which can ensure that the repetition rate of communication codes matches that of clicks, whistles and pulsed calls of killer whales, and thus achieve the camouflage of communication code sequences as much as possible. As is shown in Table 2, the TDDs between IC and IC, DA and SA, SA and SC can be set according the true TDD of killer whale calls. **Third**, as many and abundant clicks, whistles and pulsed calls as possible are used as communication codes, which can avoid the some recognizable features caused by a few clicks, whistles and pulsed calls (see Fig.11(c)). Fig. 11(a) and (b) show the TF spectrums of one communication frame transmitted in first simulation and a piece of original sound of a killer whale. It can be seen that the TF spectrum of the constructed communication frame is very close to that of original sound of a killer whale. In Fig.11(c), one single click is used repeatedly for many times as IC, and then a distinct repeated feature is generated, shown in Fig.11(c), which is very unfavorable for the promotion of camouflage concealment of the constructed communication frame.

All the above clearly indicate that the constructed communication frame has very high camouflage ability.

In the fourth simulation, we used an automatic digital modulation classification method to evaluate the security of the communication scheme. At present, many methods [60]–[62] have been proposed to automatically classify the digital modulation manners of communication information, such as 2-ary amplitude shift keying(2ASK), 2-ary frequency shift keying(2FSK), 2-ary phase shift keying(2PSK), 16-ary quadrature amplitude modulation (16QAM) and so on. Moreover, these classification methods are usually used by eavesdroppers of the adversary. In this simulation, we chose an

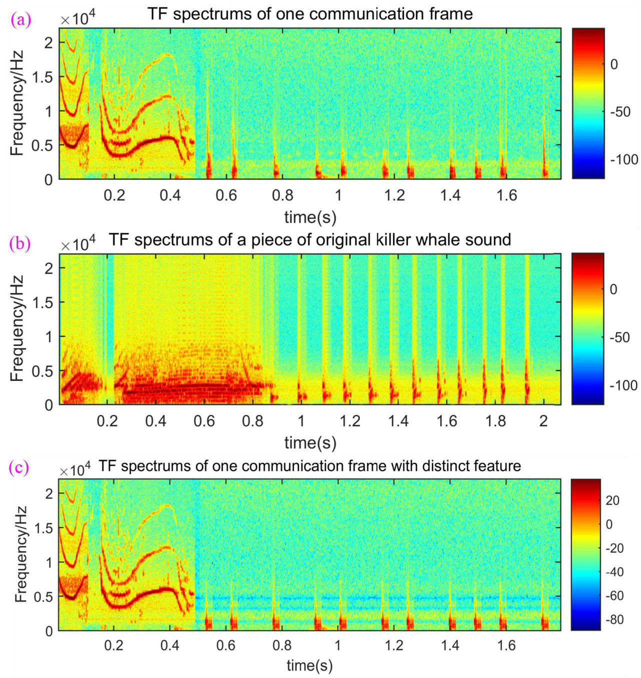

FIGURE 11. (a) The TF spectrums of one constructed communication frame, (b) the TF spectrums of a piece of original killer whale sound, (c) the TF spectrums of one communication frame with distinct feature.

universal classification method [60] to recognize the communication code sequences, and then decode them. And, the symbol error rate (SER) is used to evaluate the ability of classifying and decoding the communication information.

Three segments of 10 seconds time length communication sequences with 2ASK, 4PSK, 16QAM modulation respectively, and a segment of 10 seconds time length true killer whale call sequence are used to extract features, and these feature are used to train the artificial neural networks (ANN). Then, the trained ANN is utilized to recognize the other three segments of 1000 seconds time length communication sequences with 2ASK, 4PSK, 16QAM modulation respectively and another segment of 1000 seconds time length constructed camouflage communication sequence. Then, based on the recognition results, the communication information is decoded. The recognition probability is shown in Fig.12(a), and the SERs are shown in Fig.12(b). From Fig.12(a), one can see that when SNR is more than -5dB, the constructed camouflage communication sequence is almost always classified as the true killer whale call pulse sequence, which demonstrate that the classifier could not distinguish the constructed

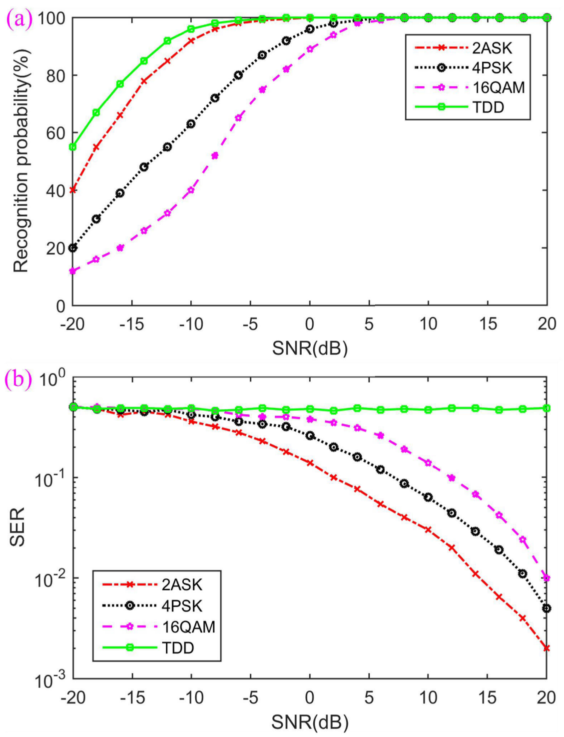

FIGURE 12. (a) The recognition probability of four different modulation manners, (b) the SERs for four different modulation manners.

camouflage communication sequence and true killer whale call pulse sequence. This is because that the constructed camouflage communication sequence uses the true killer whale pulses as the communication codes and imitates the TDDs between the true call pulses to encode the communincation information, and thus obtains very high camouflage ability. However, owing to the communication sequences with 2ASK, 4PSK and 16QAM modulation are known for the classifier, and thus obtain high recognition probability when SNR is more than 0dB. From Fig.12(b), it can be seen that the communication sequences with 2ASK, 4PSK and 16QAM modulation can be decoded accurately as the SNR increases, which is because that they are known for the classifier. However, the constructed camouflage communication sequence can not be decoded, which is because that it is recognized into the true killer whale sequence.

VII. OPEN RESEARCH ISSUES

In this article, an interesting BBICCF is design for secure underwater communication among MUPs, and it can bring out some important research directions including, but not limited to, the following.

First, in the ocean, more than two hundreds of marine mammals are able to vocalize. However, their sounds have their own characteristics which are different from each other. Therefore, to make the constructed communication code sequence highly imitate the characteristics of sound trains of all kinds of marine mammals, the sound characteristics of all kinds of marine mammals need to be studied deeply.

Second, the geographical distribution of all kinds of marine mammals determines which marine mammals' sounds can be used to construct the disguised communication codes in a specific marine area. Therefore, to ensure the camouflage of communication code sequences, the deep and detailed geographical distribution of all kinds of marine mammals is an open research issue.

Third, the communication rate, BER and camouflage ability are very important indexes for military communication. For the sound of each kind of marine mammal, under the condition of ensuring low BER, how to speed up as far as possible the communication rate and improve as far as possible the camouflage ability is a very key issue, which requires some other more effective communication encoding and decoding approaches are studied deeply, and requires some more better methods to be developed to improve the camouflage ability of communication, in the future works.

VIII. CONCLUSION

In this paper, we design a BBCCF for secure underwater communication among military underwater platforms. Different from using the conventional changed-parameters or low SNR communication codes, the presented strategy designs a disguised underwater covert communication frame by using the original, disguised and concealed whistles/pulsed calls and clicks of marine mammals to serve as communication address codes and information codes respectively, and by constructing the disguised communication frame according to the characteristics of original call pulse trains of killer whales, to cheat the enemy. Therefore, according to actual application requirements, the SNR of the transmitted communication codes can be set to a very high for a long distance communications. What's more, when there is a short communication distance, the transmitter can surely transmit the communication codes with low SNR so as to enhance the covertness by simultaneously depending on the low SNR and camouflage. The BBICCF can be extended among other static underwater communication platforms for communication networks besides the moving platform formation. This paper should be able to bring a great number of open research issues for disguised and covert underwater communication network design by using the marine mammals' sounds.

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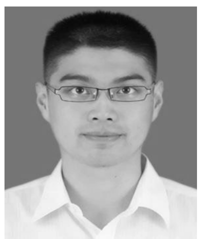

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