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Mimicking Ship-Radiated Noise With Chaos Signal for Covert Underwater Acoustic Communication

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ABSTRACT With the increasingly fierce competition for marine resources, underwater acoustic communication as the main form of underwater communication, its security has received more and more attention. The traditional underwater acoustic communication technology with fixed frequency and modulation may cause information leakage and location exposure of the communicating platform. The communication based on ocean noise is helpful to improve the communication security. This article proposes a new covert underwater acoustic communication scheme based on ship-radiated noise and chaos signal. Firstly, the characteristics of chaos signal is studied, which is generated by the Chebyshev sequence, and the reconstruction process of ship-radiated noise is analyzed. Secondly, we generate mimic ship-radiated noise containing the secret message based on the time and frequency feature of the chaos signal and ship-radiated noise. Finally, resampling technology is used to equalize the Doppler frequency shift, and time inversion mirror technology is used to perform multipath channel equalization. Simulation and sea experiment verify the effectiveness and feasibility of this scheme. In the sea experiments, the proposed scheme can reliably transimit over 40 per second when the communication distance is about 10km.

INDEX TERMS Underwater acoustic, ship-radiated noise, chaos signal, covert communication.

I. INTRODUCTION

With the exploitation and utilization of marine resources, such as marine environmental monitoring, natural disaster warning [1], [2], higher requirements are put forward for underwater transmission of information. As one of the important methods, underwater acoustic communication (UAC) has attracted extensive research in recent years. In the past few decades, the UAC technology has made great strides in communication rate and communication distance. However, with the increasingly fierce competition in marine resources, researchers have paid more and more attention to the reliability of underwater acoustic communication. The covert underwater acoustic communication (CUAC) can not only ensure the secure transmission of the secret message but also ensure that the location of the underwater communication platform is not exposed.

The traditional CUAC mainly realizes the concealment of underwater acoustic communication from two aspects. The first method is to conceal communication signal by making the enemy unable to receive the communication signal. At present, this kind of CUAC method is realized through transmission control and signal modulation.It can form the transmitting signal with certain directivity by using appropriate transducer structure, array design and occlusion technology. The power and emission angle make the detector unable to receive the communication signal. However, it is difficult to obtain the orientation and distance of the communication party in advance, and the transmission module is quite difficult to design. In addition, the application of spread spectrum technology is combined with acoustic carrier communication to maintain a low signal to noise ratio (SNR)

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of the receiver and hide the communication signal in the marine environment. At present, multi-carrier OFDM [3], [4], direct sequence spread spectrum (DSSS) [5] and multi-carrier spread spectrum (MC-SS) [6] techniques have been proposed to achieve the purpose of CUAC. However, these communication signals can eventually be detected by performing integration for a sufficiently long time, and the low received signal SNR may degrade communication performance including communication rate and distance. In addition, artificially modulated signals represent a special sound feature in the marine environment that is likely to be identified as communication signal.

The anothor method is to generate communication signals by utilizing the acoustic signals inherent in the marine environment. When the communication signal is detected by the enemies, they will be ignored as marine environmental noise. The most typical example is the bionic camouflage underwater acoustic communication technology. In [7], a bionic communication method was proposed based on the time and frequency modulation feature of dolphin whistles, a series of segmented chirp rate modulated signals were designed to mimic the dolphin whistles. Liu [8] analyzed the sound of dolphins, the dolphin whistle was used for synchronization, and the dolphin click sound was used as the information carrier. The time interval between dolphin clicks conveys message bits. Bit error rate (BER) is less than 10^{-4} with 37 bits per second data rate in the lake trial. Jia used the voice of a sea lion to realize bionic underwater acoustic communication [9]. This method used the sea lion voice as the communication signal and used the bi-orthogonal modulation method to modulate the message with the sea lion voice. The feasibility of the method was verified by simulation.

From the perspective of research status, the technology of CUAC based on marine environmental noise remains to be studied. The CUAC method based on the marine noise can generally be divided into two categories: the first is to directly use the original marine noise source as communication signal [8], [9] and the second is to use the composite signal or the mimic sound source as the communication signal for communication [7]. At present, most of the CUAC method based on the marine noise is to mimick the sound of various marine mammals, among which the click and whistle are the main sound. However, due to the certain living habits of marine mammals, such covert communication methods have certain limitations in use. Relatively, ship-radiated noise appears in a wider range, and it is more difficult to arouse the suspicion of the enemy.

At present, the most effective underwater communication techniques is acoustic-based. To realize secure and covert underwater acoustic communication, we propose a covert underwater acoustic communication scheme in this article. In the proposed scheme, the communication signal is disguised as the ship-radiated noise signal to transmit message, making the communication signal can not be distinguished from the normal ship-radiated noise by the detector, which is quite different from the traditional spread spectrum communication schemes. Moreover, compared with some exsting covert bionic underwater communication schemes, the implemention limitation of the proposed scheme is significantly small. By using the correlation of the chaos signal, the secret message is embedded, and corresponding pilot and synchronization signals are added into the communication signal. By analyzing the ship-radiated noise, the continuous spectrum, line spectrum and envelope function are extracted, and the ship-radiated noise is reconstructed to generate the covert communication signal. The receiver uses the pilot signal to detect the underwater acoustic channel and realizes Doppler shift compensation and multipath equalization. Due to the characteristics of chaos signals, the scheme has unique advantages in channel processing. The proposed communication system has a low BER in the complex underwater acoustic channel and can resist multipath and Doppler channel interference. Because the communication signal of the scheme is the reconstructed mimic ship-radiated noise, the scheme can guarantee the transmission accuracy and realize the secure underwater acoustic communication. The main contributions are summarized below.

1. The underwater acoustic communication signal is first disguised as ship-radiated noise in this study, which provides a potential application scenario for covert underwater acoustic communication.

2. A novel covert underwater acoustic communication scheme based on the correlation of chaos signals is proposed, which can achieve both strong robustness and high undetectability. In addition, the modulation method can also be employed for other types of underwater enviromental noise to design robust covert communication schemes.

3. Detailed simulation and actual experimental results are presented in this study to veritify the effectiveness of the proposed covert underwater acoustic communication scheme.

II. RELATED WORK

A. COVERT UNDERWATER ACOUSTIC COMMUNICATION

In this section, we briefly describe several proposed covert underwater acoustic communication schemes based on acoustic camouflage and chaos signal.

1) UNDERWATER ACOUSTIC CHAOTIC SPREAD SPECTRUM COMMUNICATION

Ren [10] proposed a spread-spectrum covert underwater acoustic communication scheme based on chaos sequences, chaos sequences are employed as the spread-spectrum sequences of the spread-spectrum communication system instead of pseudo-random code sequences to achieve covert underwater acoustic communication. A hybrid dynamical system comprising of a continuous state u and a discrete state s are discussed as: $\ddot{u} - 2\beta\dot{u} + (\omega^2 + \beta^2)(u - s) = 0$. Where, $\omega = 2\pi f$, $\beta = f \ln 2$, and $f (f = 1, 2, 3, \ldots)$ denotes the base frequency of the signal.

As shown in Fig. 1, firstly, the module converts the binary message $(B_1, B_2, \ldots, B_M)$ into the corresponding continuous

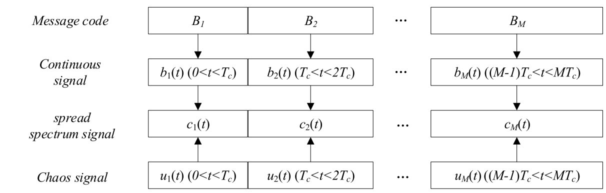


FIGURE 1. The generation process for the spread spectrum signal.

signal $(b_1(t), b_2(t), \ldots, b_M(t))$, which represents binary message 1 with amplitude equal to one and binary message 0 with amplitude equal to negative one. Each message bit has time duration T_c. Secondly, the spread spectrum signal $c(t)$ is derived by multiplying the rectangular waveform with the signal $u(t)$ generated by hybrid system. Thirdly, the spread spectrum signal $c(t)$ is incorporated with the synchronous frame, which is a piece of $u(t)$.

At the receiver, the signal is firstly filtered with the pre-matched filter [11] to obtain the equalized signal $\hat{c}(t)$. The symbols embodied in $\hat{c}(t)$ can be detected by $\hat{s}_n = \text{sign}(c(nT_c))$. After the symbols $\hat{s}_n$ are detected, according to the rule of the synchronization frame selection and incorporation, the transmitted binary bits can be decoded by multiplying the synchronization symbol and its corresponding symbol of the spread sequence in the filtered signal $\hat{c}(t)$.

In this scheme, the chaos signal generated by hybrid power system is used as the spread spectrum sequence, and a new chaotic spread spectrum underwater acoustic communication method is proposed to realize reliable underwater acoustic communication. However, after a long enough time of integration, these communication signals can be detected, and the low SNR of the received signal will degrade the communication performance.

2) BIOLOGICALLY INSPIRED COVERT UNDERWATER ACOUSTIC COMMUNICATION BY MIMICKING DOLPHIN WHISTLES

Liu [7] analyzed the contour feature of dolphin whistle sound, and studied the underwater acoustic communication technology of the dolphin whistle based on parametric model modeling. According to the time and frequency modulation characteristics of dolphin whistle, a series of segmented chirp rate signals were designed to simulate dolphin whistle by using the sound characteristics. As shown in Fig. 2, a special communication frame structure is designed. The original whistle is used as synchronization signal to transmit information. In addition, the original synchronous whistle is used as the transmission reference to extract the contour of the whistle, and then the center frequency of each chirp is obtained. So the i_{th} chirp modulated signal $S_i(t)$ is given by $S_i(t) = cos(2\pi t(f_{ci} - d_i * \frac{kT}{2}) + d_i * \pi k t^2)$. Where, f_{ci} is the center frequency of i_{th} chirp signal, d_i is the i_{th} code, k is the chirp rate. When d_i=1, $S_i(t)$ is the up chirp, and $d_i = -1$, $S_i(t)$ is the down chirp. After synchronization, all the chirp codes are extracted and the fractional fourier transform value of each received chirp is computed and compared to decide the message code.

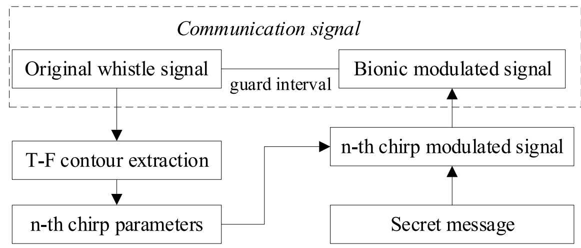


FIGURE 2. Frame structure and modulation process.

The scheme realizes covert underwater acoustic communication by disguising the underwater acoustic communication signal as dolphin sound. However, the scheme will be affected by the dolphin's living habits, so the application of the scheme is limited. However, the scheme will be affected by the living habits of dolphins, which limits the use of the scheme. In this article, we disguise the communication signal as ship-radiated noise, which can effectively solve the limitation of use scenarios.

B. UNDERWATER ACOUSTIC CHANNEL EQUALIZATION TECHNIQUE

Underwater acoustic channels are usually disturbed by multipath, time-varying and frequency-varying interference. The traditional decision feedback method is applied in [12] as the channel equalization method. In addition, for the communication signal of a specific design, the method of matching filter [11] is proposed to equalize the channel in [13]. At present, Doppler frequency shift equalization and virtual time reversal mirror are widely used in underwater acoustic communication. In this article, we will adopt these two methods as the channel equalization scheme.

1) THE VIRTUAL TIME REVERSAL MIRROR CHANNEL EQUALIZATION

The theory behind time reversal [14]–[16] has been presented earlier. The virtual time reversal mirror (VTRM) technology estimates the channel impulse response by the received pilot signal, convolves the received signal with the estimated channel time reversal, and achieves equalization of the communication channel. This method is mainly used to eliminate the multipath interference in the underwater acoustic channel [17].

Considering an underwater acoustic communication system, the transmitter and receiver share the pilot signal $p(t)$, and the transmitter transmits the pilot signal $p(t)$ and the communication signal $g(t)$. The channel impulse response is $h(t)$ and the channel noise is $n(t)$. The pilot signal $p'(t)$ and the communication signal $g'(t)$ are received:

$$
\begin{aligned}
p'(t) &= p(t) \otimes h(t) + n(t) \\
g'(t) &= g(t) \otimes h(t) + n(t) \qquad (1)
\end{aligned}
$$

The process of VTRM is performed as follows: At the receiver, the channel impulse response $h'(t)$ could be estimated with (2); Reverse its time and make convolution with the received information signal $g'(t)$ as shown in (3).

$$\begin{aligned}\hat{p}(t) &= p'(t) \otimes p(-t)\\ &= p(t) \otimes h(t) \otimes p(-t) + n(t) \otimes p(-t)\\ &= h'(t) \approx h(t) \end{aligned} \tag{2}$$

$$\begin{aligned}\hat{g}(t) &= (g(t) \otimes h(t) + n(t)) \otimes h'(-t)\\ &= g(t) \otimes [h(t) \otimes h'(-t)] + n(t) \otimes h'(-t)\\ &\approx g(t) \end{aligned} \tag{3}$$

When the pilot signal has a good self-correlation, $h'(t)$ approaches $h(t)$ and energy overlap of multipath signals leads to convergence effects. Due to the simple and efficient realization of the VTRM, it is widely used in underwater acoustic communication. Therefore, this article also adopts the VTRM to eliminate the influence of multipath on communication.

2) DOPPLER SHIFT ESTIMATION AND COMPENSATION

Due to the acoustic scattering of the undulating sea surface and the relative motion between the transmitter and the receiver, The Doppler effect occurs in the received signal. The Doppler shift of underwater acoustic channel has a negative effect on the synchronization and demodulation of underwater acoustic communication system [18].

For the broadband signal, the Doppler effect causes different frequency components to have different frequency shifts. Therefore, the compression and expansion of the signal in time to describe the Doppler frequency shift is more accurate, as shown in (4).

$$r(nT_s) = s[n(1 + \Delta)T_s]. \tag{4}$$

where T_s is the sampling period and Δ is the relative Doppler shift.

In the process of Doppler shift estimation and compensation, the transmitter and receiver share the pilot signal. Copies of pilot signals with different Doppler frequency shifts are generated at the receiver according to (4). It is known that the correlation coefficient between pilot signals for different Doppler frequency shifts is low, so different copies of pilot signal are calculated with the received pilot signal to calculate the correlation coefficient, and the Doppler frequency shift corresponding to a larger correlation coefficient is the Doppler frequency shift of the communication channel. The Doppler frequency shift equalization is compensated by (4) according to the inverse of the obtained channel Doppler frequency shift.

III. CHAOS SIGNAL AND SHIP-RADIATED NOISE

A. THE CHARACTERISTIC OF CHAOS SIGNAL

The chaos signal [19], [20] is a non-periodic bounded signal generated by a deterministic system. It has characteristics sensitive to initial values and exhibits noise-like characteristics in the time domain and broadband characteristics in the frequency domain. Studies show that chaos sequences have good balance and correlation [21], [22].

Among many methods of generating the chaos signal, the Chebyshev map is one of the most commonly used methods of generating the chaos sequence. Its chaos sequence satisfies the mean value of zero and has good self-correlation. For the Chebyshev map, when the initial value changes by 10^{-16}, two mutually unrelated sequences can be generated. Compared with other generated sequences, the Chebyshev sequence can meet the needs of communication better. The Chebyshev sequence is defined as follows:

$$x(n+1) = f[x(n)] = \cos\{w * ar\cos[x(n)]\}. \tag{5}$$

where $-1 \leqslant x(n) \leqslant 1$, w refers to the control parameter. When the parameter is not less than 2, the Chebyshev map can enter the chaotic region and produce an infinite length of non-periodic chaotic real sequences under infinite precision conditions [23].

1) CORRELATION CHARACTERISTICS OF THE CHEBYSHEV SEQUENCE

In this section, we set the sampling rate to 44.1 kHz to analysis the self-correlation and cross-correlation characteristics of the Chebyshev sequence. The correlation of the Chebyshev sequence is shown in Fig. 3.

As shown in Fig. 3(a), the initial value $x(0)$ is set to 0.2 and the control parameter w is set to 20, which shows an impulse like with a fast exponential decay self-correlation function. The cross-correlation in Fig. 3(b) describes the correlation coefficient between chaos sequences initialized with 0.005 and other initialized values (ranged from 0.01 to 0.995) which can prove that the correlation of chaos sequences for different initial values is very weak.

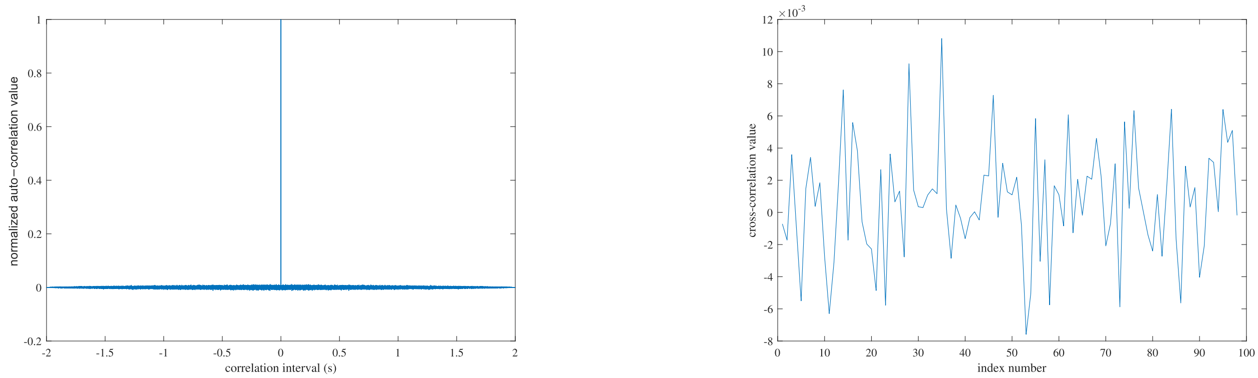
In this article, in order to reconstruct the ship-radiated noise, we need to filter the chaos signal. Table 1 lists the normalized self-correlation coefficients and cross-correlation coefficients of the chaos sequences with different initial values after passing through the filter. From Table 1, we can ascertain that the correlation coefficients between the signals for different initial values is very weak(less than 0.0294).

TABLE 1. The normalized self-correlation and cross-correlation coefficients of each signal.

	C1	C2	C3	C4	C5	C6	C7	C8
C1	1	0.0131	0.0101	0.0003	0.0149	0.0115	0.0071	0.0294
C2	0.0131	1	0.0087	0.0125	0.0075	0.0102	0.0063	0.0015
C3	0.0101	0.0087	1	0.0029	0.0007	0.0278	0.0195	0.0123
C4	0.0003	0.0125	0.0029	1	0.0027	0.0255	0.0143	0.0040
C5	0.0149	0.0075	0.0007	0.0027	1	0.0107	0.0051	0.0002
C6	0.0115	0.0102	0.0278	0.0255	0.0107	1	0.0123	0.0014
C7	0.0071	0.0063	0.0195	0.0143	0.0051	0.0123	1	0.0219
C8	0.0294	0.0015	0.0123	0.0040	0.0002	0.0014	0.0219	1

2) FREQUENCY DOMAIN CHARACTERISTICS OF THE CHEBYSHEV SEQUENCE

Fig. 4 shows the time-frequency distribution of the Chebyshev sequence using the short-time Fourier transform. From the distribution, we can find the spectrum of the Chebyshev sequence does not change with time, and its power remains the same at each frequency point. The power spectral density



(a) Self-correlation (b) Cross-correlation

FIGURE 3. The correlation characteristics of Chebyshev sequence.

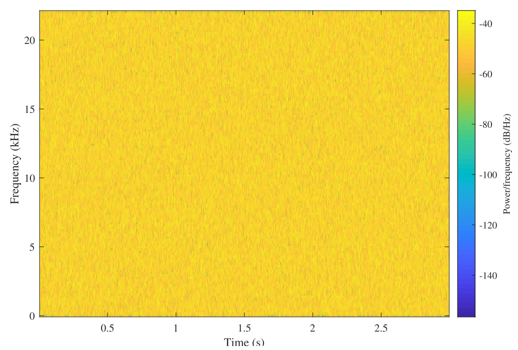


FIGURE 4. The time-frequency distribution of chaos signal.

of the Chebyshev sequence is uniformly distributed. The Chebyshev sequence can be used to generate noises with specific frequency characteristics.

B. SHIP-RADIATED NOISE

As an important part of marine environment noise, ship-radiated noise [24], [25] has a high level of sound source and universality, which makes it a better UAC signal. Fig. 5 shows the time and frequency domain figure of a merchant ship. It can be seen from Fig. 5(a) that the ship-radiated noise is an uncertain signal, and its uncertainty is most obvious in the time domain waveform. It is difficult to directly simulate ship-radiated noise in time domain. However, the spectrum of ship-radiated noise is composed of continuous spectrum and line spectrum. The mathematical model [26] of the time-domain waveform of ship-radiated noise can be composed of the time domain signals corresponding to the continuous spectrum and the line spectrum:

$$S(nT_s) = [1 + a(nT_s)]G_c(nT_s) + G_l(nT_s). \tag{6}$$

where $G_c(nT_s)$ is the time domain waveform corresponding to the amplitude-frequency characteristics of original ship-radiated noise; $a(nT_s)$ is the modulation function, which is obtained by filtering, detecting and spectral analysis of radiated noise, and its amplitude is small; $G_l(nT_s)$is the time domain waveform corresponding to the line spectrum component. Line spectra are concentrated in infrasound and low frequency bands, with the dominant frequency bands of the continuous spectrum ranging from a few Hertz to tens of thousands of Hertz. The reconstruction of ship-radiated noise can be realized through the following three steps:

(1)The time domain waveform corresponding to the amplitude-frequency characteristics of original ship-radiated noise can be fitted by a stable random process with broad-band, as shown in Fig. 6. First, based on the ship-radiated noise, the amplitude-frequency characteristics are extracted, and the FIR filter with a specific frequency response is designed. The chaos signal is passed through the FIR filter to generate noise S_c with amplitude-frequency characteristics of the ship-radiated noise.

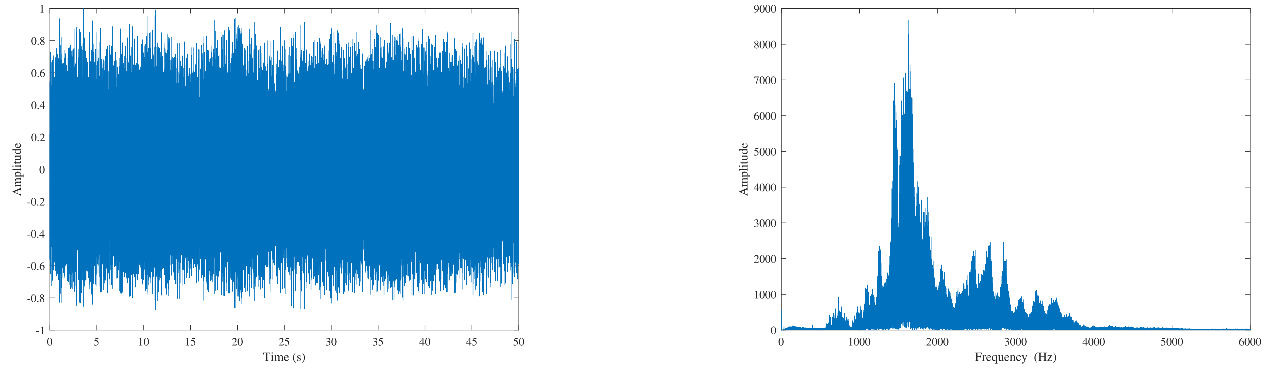
(2)The envelope spectrum cannot only obtain important recognition information such as target speed and number of blades but also has better robustness of harmonic line spectrum characteristics, which is helpful for target type recognition. The general model of envelope analysis is shown in Fig. 7. Ship-radiated noise is generally a wide-band signal. The time domain signal of noise must be filtered firstly, and then Hilbert transformation and low pass filter are applied to the filtered signal to obtain the envelope of ship radiated noise. The noise S_e with the continuous spectrum characteristic of ship-radiated noise can be obtained through envelope modulation.

(3)Line spectrum components can be simulated by generating a series of sinusoidal signals, as shown in (7)

$$G_l(nT_s)= \sum_{k=1}^{k=K} A_k \sin(2\pi f_k nT_s + \phi_k). \tag{7}$$

where K is the number of line spectrum, A_k, f_k and ϕ_k are the amplitude, frequency, and random phase. The line spectrum is directly related to the number of blades and the speed of propeller. Set line spectrum frequency $f_k = mns$, where m is the harmonic number; n is the number of propeller blades; s is the propeller speed.

The line spectrum is mostly distributed in the low-frequency band, and the frequency is relatively stable, which is the main feature in identifying the shape of the ship.



(a) Time domain (b) Frequency domain

FIGURE 5. The time and frequency domain diagram of a merchant ship.

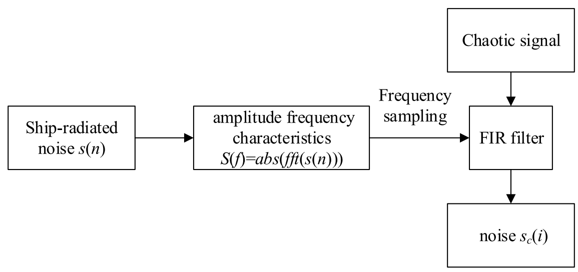


FIGURE 6. Reconstruction of time domain waveform corresponding to continuous spectral components.

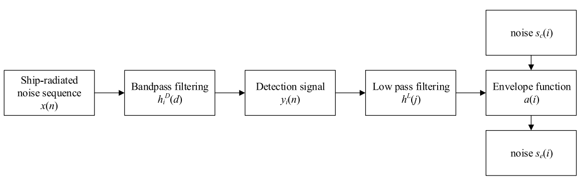


FIGURE 7. The general model of envelope spectrum analysis.

For the line spectrum generated by the propulsion system and propeller, its amplitude and frequency vary with the speed of the ship. As the frequency increases, the continuous spectrum will mask the line spectrum. Hence, we consider the low-frequency line spectrum below 100Hz. A merchant ship whose line spectrum is shown in Fig. 8.

IV. PROPOSED METHOD

Based on the correlation characteristics of the chaos signal, this article proposes the covert underwater acoustic communication scheme based on mimic ship-radiated noise(CUACS). Comprehensive modulation, equalization and demodulation approach are also discussed in this section.

A. FRAME STRUCTURE

The CUACS scheme frame in this article is shown in Fig. 9. In our scheme, the chaos signal is selected to generate the communication signal according to the secret message. The mimic ship-radiated noise containing the secret message is transmitted through the communication channel. First, the synchronization signal is use to capture the communication signal. Then, the pilot signal is used to equalize the channel to recover the communication signal. Finally, the secret message is demodulated by the correlation demodulation. The receiver and transmitter share the original ship-radiated noise and the initial value of chaos signal used to realize covert communication.

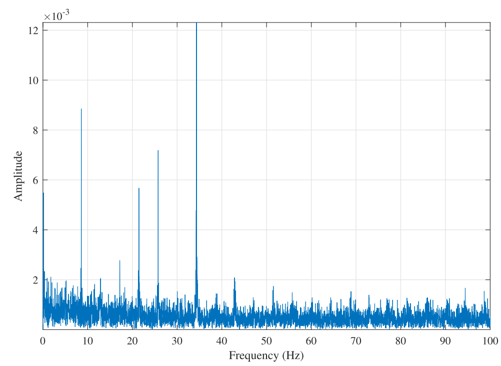


FIGURE 8. The line spectrum of a merchant ship.

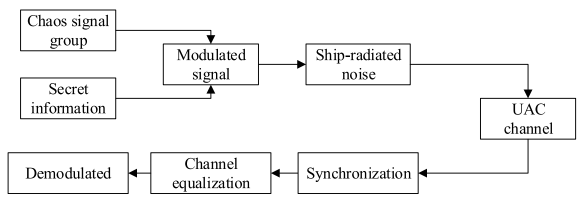


FIGURE 9. Block diagram of the proposed CUAC scheme.

B. MODULATION SCHEME

In this section, we introduce the modulation scheme for the CUACS scheme. We have analysis the characteristics of chaos signal and ship-radiated noise in section 3. The time domain waveform corresponding to the continuous spectral components of ship-radiated noise can be generated by using chaos signals. In this article, The chaos signal with an initial value of 0.99 is generated as the synchronization signal. The chaos signal with an initial value of 0.98 is used as the pilot signal. The chaos signal group with an initial value of 0.01:0.01:0.64 is used to embed the secret message, and we set group numbers from 0 to 63.

The modulation process is divided into two parts: the secret message modulation process and ship-radiated noise reconstitution process. The process flow chart of the secret message modulation is shown in Fig. 10.

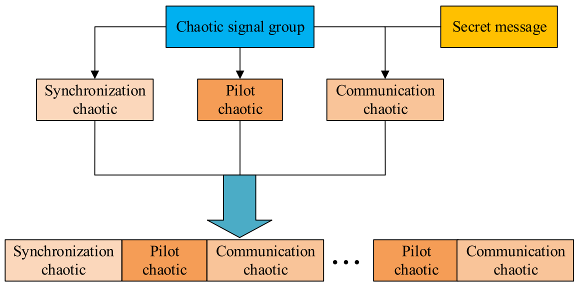


FIGURE 10. The structure process of communication chaos sequence.

The CUACS signal consists of three parts: the first part is the synchronous signal, which is used to capture communication signal; the second part is the pilot signal, which is used to probe the channel environment and equalize the channel effect; the last part is the communication signal containing the secret message. In the secret message modulation process, the binary secret message is first encoded and converted to a decimal number every six codes. Chaos signals with different initial values are selected according to the decimal number. For example, if the sending message is '000000', select group 0 chaos signal; if the sending message is '111111', select group 63 chaos signal.

In order to prevent the influence of time-varying channel on information demodulation, the pilot signal is inserted between communication signals every 10 seconds. For the convenience of receiving and demodulation, the length of each set of communication signals is the same, so is the length of all pilot signals.

According to the time-frequency characteristics of the ship-radiated noise, the mimic ship-radiated noise containing the secret message is generated. The flow chart of ship-radiated noise reconstruction is shown in Fig. 11. Firstly, the amplitude-frequency characteristics, line spectrum and envelope of the original ship-radiated noise are obtained. The corresponding FIR filter is designed according to the amplitude-frequency characteristics and the chaos signal is filtered by the designed FIR filter to obtain the time domain waveform. According to the envelope function, the envelope modulation is applied to the time domain waveform corresponding to the continuous spectrum. Finally, according to the obtained line spectrum, the time domain waveform corresponding to the line spectrum is formed by (7), and the waveform is superimposed on the time domain waveform corresponding to the continuous spectrum to reconstruct the ship-radiated noise.

C. DEMODULATION APPROACH

The demodulation process of the scheme includes three parts: signal synchronization process, channel estimation and

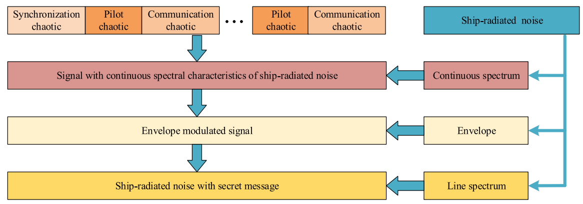


FIGURE 11. Generation process of the mimic ship-radiated noise.

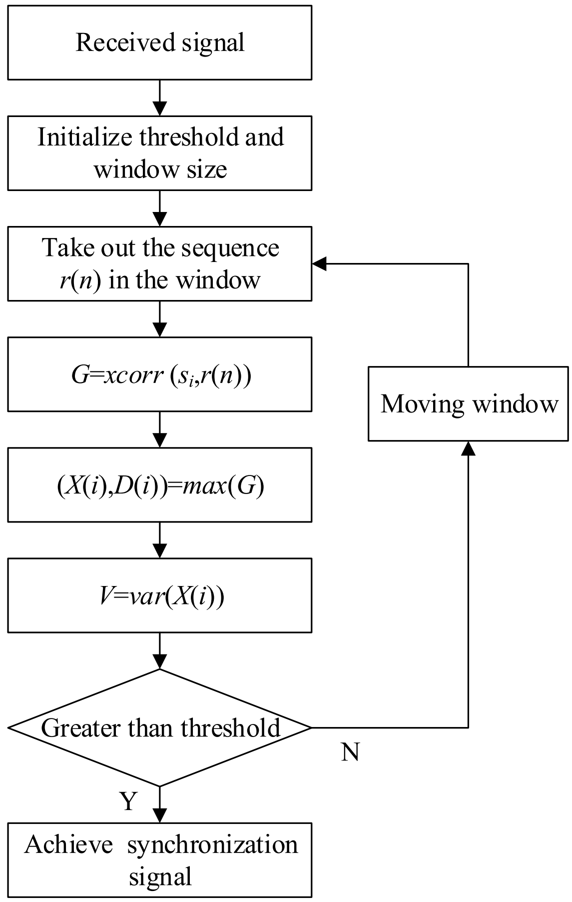


FIGURE 12. The flowchart of synchronous acquisition.

equalization, and message demodulation process. The specific demodulation method will be described in detail in this section.

1) SYNCHRONOUS ACQUISITION

In the proposed scheme, a 5-second mimic ship-radiated noise is used as the synchronization signal. Because the Doppler frequency shift has a great influence on the correlation of the signal, we generate the copies (S_i) of synchronous signal with different Doppler frequency shifts at the receiver. The synchronization process is shown in Fig. 12.

The specific steps are as follows:

(1) The window size is twice the length of the synchronization signal, and the received signal through this window;

(2) The copy $S_i(i = 1, \ldots, N)$ of synchronization signal is convolved with the sequence in the window to obtain the

maximum value $X(i)$ and record the maximum value position $D(i)$ is the number of copies of synchronization signal;

(3) The variance V of X is calculated. When there is a synchronization signal in the window, the correlation value for the copy group of synchronization signal is significantly larger, which results in a large variance value V. When the variance V is greater than the threshold T and the maximum value position $D(k)$ is in the first half of the window (where $X(k) = \max(X)$), then the signal synchronization position is $D(k)$. Otherwise, the window moves backward the length of the synchronization signal and returns to step (2).

2) CHANNEL EQUALIZATION

To suppress the impact of complex underwater acoustic channels on communication performance, we set the pilot signal between the communication signals; the pilot signal is shared by the receiver and transmitter. In this article, channel equalization includes Doppler frequency shift equalization and multipath equalization.

The measures for Doppler equalization are as follows:

(1) Generating the copies of the pilot signal with different Doppler frequency shifts at the receiver. The correlation coefficient between the copies and the received pilot signal are calculated respectively;

(2) Obtaining the maximum correlation coefficient and the frequency shift of the copy with the maximum correlation coefficient is the Doppler frequency shift of the communication channel;

(3) According to the estimated channel Doppler frequency shift, Equation (4) is used to equalize the communication signals.

Multipath equalization of the signal after Doppler equalization:

(1) The pilot signal is convolved with the received pilot signal after Doppler equalization;

(2) Set the threshold to extract the impulse response;

(3) Perform multipath equalization on the received signal according to (3).

3) DECODING PROCESS

In this article, we use the correlation of the chaos signal to embed the secret message. The demodulation scheme demodulates the information according to the correlation coefficient of the received signal, and the specific demodulation steps are shown in Fig. 13:

The correlation coefficients of the received signal and the 2^n - group communication signals are calculated respectively. The communication signals are reconstructed from chaos signals according to time-frequency characteristics of ship radiated noise. The group number m of the maximum correlation coefficient is obtained, then the demodulation result is the binary number corresponding to m.

V. SIMULATION AND EXPERIMENT

In this section, we analyze the BER performance of the proposed covert communication scheme in the underwater acoustic channel, and the similarity between the communication signal and the original ship-radiated noise. The effectiveness of the proposed scheme is verified by communication experiments in the sea.

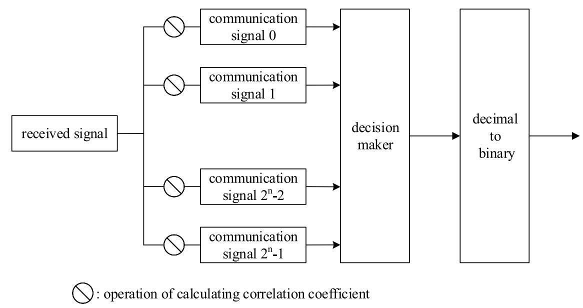


FIGURE 13. The demodulation steps of the proposed method.

A. SIMULATION SETUP

In this article, the bellhop ray model developed by M. Porter is used to generate a fixed multipath channel model for simulation, and Gaussian noise and Doppler frequency shift are added.

TABLE 2. Bellhop model environment parameters.

Parameter name	Parameter value
Propagation distance	20km
Speed of sound in Sediment	2000m/s
The acoustic absorption coefficient of seawater	6.93e-05~6.94e-05dB/km
Sound source depth	20m
Depth of seawater	50m
Sediment density	$1.81 g/m^3$
Speed of sound in the sea	1540m/s~1543m/s
Arrival angle of the sound line	$-15° \sim 15°$
Sea water density	$1.021 g/cm^3$
Depth of reception	20m

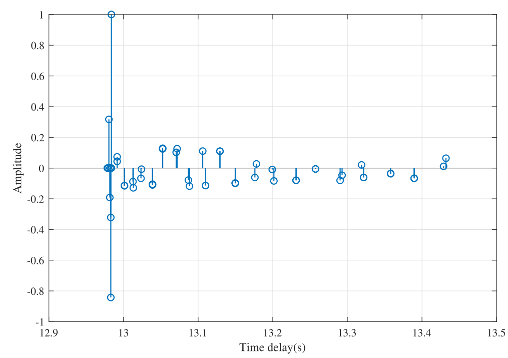


FIGURE 14. The impact response of Bellhop model.

In this article, based on the bellhop model and MATLAB software, multipath channel with different signal frequencies under the condition of fixed transmitter and receiver nodes are generated, which are used in simulation to verify the feasibility of the proposed communication method. The environmental parameters of the bellhop model are shown in Table 2. The impact response of the simulation channel is shown in Fig. 14.

In simulation, the transmission rate is set to 20, 35, 50 bps; we set the length of the pilot at 0.7 seconds; the length of the synchronization signal is 5s. Each test sends 20000 binary message.

B. SIMULATION RESULT

Considering the influence of different sound source levels on demodulation results. We mainly study the BERs for different SNR conditions to determine the communication performance of the proposed scheme. The simulation is conducted to verify the effect of VTRM equalization, and we compared the proposed scheme with the schemes in other literature. As shown in Fig. 15, the BER can be significantly improved with VTRM equalization. Compared with the covert communication scheme mentioned in [7], the proposed scheme can achieve a better communication performance.

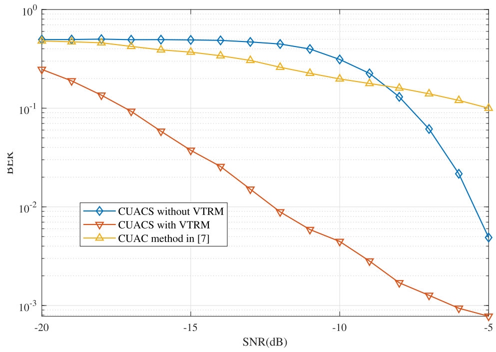


FIGURE 15. Bit error rates for the simulation results.

1) SIMULATION RESULTS WITH DIFFERENT DOPPLER SHIFTS

Because of the Doppler frequency shift of underwater acoustic channel, it will have a great influence on the demodulation of message. In this section, we add different Doppler frequency shifts in the channel to verify the effect of the Doppler equalization method.

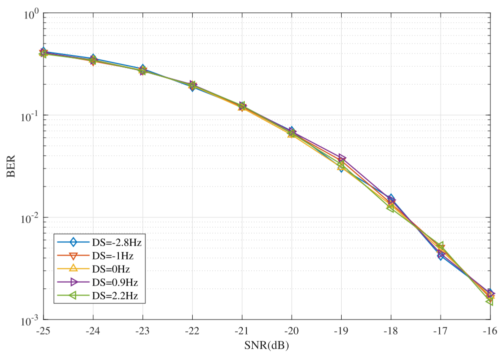


FIGURE 16. Bit error rates for different Doppler frequency shift.

As shown in Fig. 16, Doppler frequency shifts of -2.8, -1, 0, 0.9 and 2 Hz are added to the simulation respectively. The simulation results show that the BER of the proposed scheme is similar for different Doppler conditions. The Doppler equalization method can effectively resist the influence of the Doppler frequency shift on the communication effect.

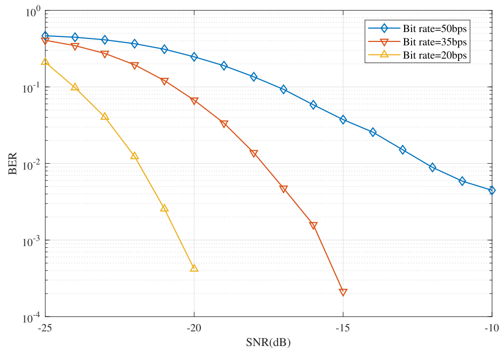


FIGURE 17. Bit error rates for different communication rates.

2) SIMULATION RESULTS WITH DIFFERENT TRANSMISSION RATES

The communication rate is an important indicator for measuring the communication. Fig. 17 shows the BERs for different communication rates. As the data rate increases, the BER decreases accordingly. In the practical application process, in order to achieve efficient and accurate communication, the appropriate data rate should be selected according to the communication requirement.

3) SIMILARITY ANALYSIS

In this section, we analyze the power spectral density of ship-radiated noise and the CUACS signal to verify whether there is an obvious difference between them. Fig. 18(a) shows the power spectral density of the merchant ship and the CUACS signal based on this ship-radiated noise. The analysis of fishing-boat is shown in Fig. 18(b). The power spectral density of the signal does not change significantly after modulation, and the CUACS signal maintains the time-frequency characteristic of the original ship-radiated noise.

C. SEA EXPERIMENT

To evaluate the performance of the covert underwater acoustic communication system, the sea experiment was carried out in July 2019. In the experiment, the transmitting ship was anchored in the sea, and the receiving ship drifted with the wave. The depth of the sea is about 50 meters, the transmitting transducer is about 25 meters above the water, and the receiving hydrophone is at the same depth as the transducer. In order to achieve accurate communication in the marine environment, the length of synchronous signal is adjusted to 5s, and that of pilot signal is adjusted to 1s.

The sound speed profile measured in the sea experiment is shown in Fig. 19. The sound velocity in the sea area is a negative gradient at a depth of 0 $\sim$ 3 m, an equal sound velocity distribution at a depth of 3 $\sim$ 10 m, and a negative gradient layer at a depth of 10 $\sim$ 45 m. The sound velocity gradient in the sea area shows a negative gradient, which has a great impact on sound propagation. Most of the sound rays will hit the ocean floor and be absorbed by the ocean floor, resulting in a large loss of acoustic energy, which is not conducive to sound transmission.

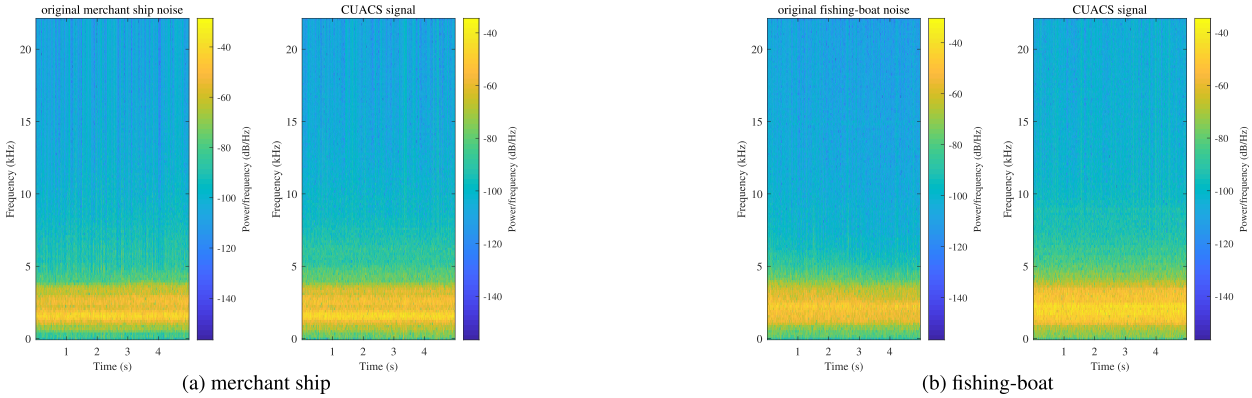


FIGURE 18. **Time-frequency diagram of ship-radiated noise and CUACS signal.**

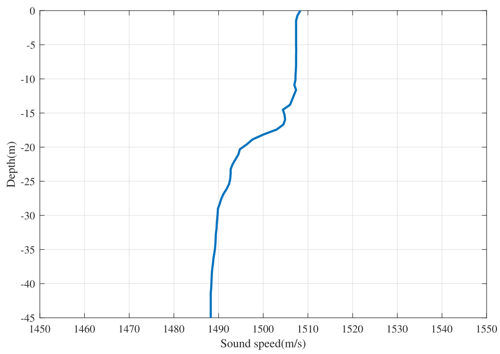


FIGURE 19. **The sound speed profile measured in the experiment.**

TABLE 3. **The demodulation results of the sea experiment.**

Distance(km)	Rate(bps)	Ship-radiated noise	BER
5	20	fishing-boat	0
5	20	merchant ship	0
5	40	fishing-boat	0
5	40	merchant ship	0
10	20	fishing-boat	0
10	20	merchant ship	0
10	40	fishing-boat	0.00399
10	40	merchant ship	0.0025

BERs in the sea experiment are shown in Table 3 for different communication distances, communication rate and ship-radiated noise. Experiments in the sea further verify the effectiveness of our scheme, and we can still communicate accurately when there is relative motion between the transmitter and the receiver.

VI. CONCLUSION

According to the characteristics of chaos signal and ship-radiated noise, a CUAC scheme based on ship-radiated noise is proposed. Compared with the traditional CUAC scheme, the CUACS scheme uses the correlation of chaos signal to transfer the message and the communication signal is disguised as ship-radiated noise to resist the detection. In this scheme, the pilot signal is used for Doppler frequency shift equalization and multipath equalization. In the simulation, the scheme can reliably transmit data at a speed of 50 per second when the SNR reaches -10dB. In the real-world experiments, the proposed scheme can reliably transimit over 40 per second when the communication distance is about 10km. This scheme can be used to achieve accurate and reliable communication over long distances. The concealment of the scheme is verified by comparing the time-frequency characteristics of the CUACS signal with the ship-radiated noise. The feasibility of the method is verified by the sea experiment. In order to improve the communication performance, the great variety of ship types and channel equalization method can be studied in the future.

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