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Chaotic modulations and performance analysis for digital underwater acoustic communications

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ABSTRACT

Two modulation schemes, M-ary phase shift keying (MPSK) and M-ary frequency shift keying (MFSK), are commonly used for coherent and incoherent digital communications, respectively. Despite wide applications in underwater acoustic (UWA) communications, they are not suitable for confidential applications for their well-known generating processes and signal features. In this paper, two corresponding chaotic modulation methods are proposed to improve their security, namely chaotic MPSK (CMPSK) and chaotic MFSK (CMFSK). By application of chaotic sequences into the modulation procedures, they can prevent the unauthorized receivers from extracting information from the intercepted signals even with high SNR. The confidential performance of chaotic modulations is evaluated by a designed automatic modulation classification (AMC) system. Simulation results indicate a success identification rate of more than 90% for the MPSK and MFSK signal at the SNR from −10 dB to 40 dB, but only an identification rate of nearly zero for the CMPSK and CMFSK signal. Therefore, chaotic modulations have lower available probability and can achieve higher confidential performance. Also, an experiment was conducted to verify the performance of chaotic modulations in actual UWA communications. The experimental results show that chaotic modulations can achieve similar bit error ratio (BER) compared with conventional digital modulations, which verifies potential applications of chaotic modulations in confidential UWA communications.

1. Introduction

Communication security has long been recognized as a challenging task in underwater acoustic (UWA) communications. Generally, secure communication has a low probability of detection (LPD), low probability of interception (LPI) or low probability of availability (LPA). LPD means a low probability that the transmitted signals are detected from the environment. LPD signal is difficult to be detected by adversaries, but its low energy degrades the communication performance simultaneously. LPI means a low probability that the transmitted signals are intercepted by enemies. Frequency-hopping spread spectrum (FHSS) is a typical modulation scheme that has a low probability of interception, but it is rarely used in the UWA communication due to the characters of UWA channel. LPA means that it is difficult for unauthorized receivers to extract useful information from intercepted signals. As the UWA channel is usually fading and complex, many communication systems work at high source level to achieve satisfying performance. As a result, the transmitted signals may be detected and intercepted by unauthorized users. So designed signals with a low probability of availability are very valuable in confidential UWA communications.

In order to achieve reliable communication over UWA channel, many techniques have been proposed so far. Direct sequence spread spectrum (DSSS) has been widely researched in UWA communications [1–3], which benefits from spreading gain to enable communications at low signal-to-noise ratio (SNR). Besides, DSSS technique has a low probability of detection by extending the signal power to much wider spectrum. It is considered as a candidate technique for confidential communications. However, the data rate of DSSS technique is quite low, which is difficult to meet the requirements of high-speed communication. In addition, the small quantity of spreading sequences, such as m-sequence and Gold sequence, is another deficiency. Some traditional digital modulation schemes, such as the M-ary phase shift keying (MPSK) and M-ary frequency shift keying (MFSK), have greater bandwidth efficiency. They have been extensively applied in UWA communications [4–7]. Besides their common usage for short and medium range communications, recently they have also been proved to be available for long-range UWA communications when modulated at a low frequency [8–10]. However, they are not ideal

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choices for confidential scenarios for their well-known generating processes and signal features. And it's not difficult for unauthorized users aware of the transmission to access the information.

Chaotic sequences possess excellent properties, such as random-like behavior, nonlinearity, sensitive to initial conditions. Besides, they have outstanding correlation properties and quite a large quantity available. Therefore, chaotic sequences are well suited for confidential communications [11–13]. After the demonstration that chaotic systems can be synchronized [14], research into applications of chaos in communications has been motivated. To date many schemes have been proposed, such as chaotic masking [15], chaos-shift keying and chaotic modulation. Chaotic masking is sensitive to noise and has low confidentiality, so it is rarely adopted in UWA communications. Chaos-shift keying schemes (CSK, COOK, DCSK, FM-DCSK, QCSK) have been widely studied over the past years [16–18]. The transmitted signal is obtained by switching between N chaotic generators according to the information message. Chaotic modulation is to modulate the parameters of chaotic signal by message bits, thus containing the information of transmitted messages [19,20]. However, the performance of previous methods is based on the self-synchronization property of chaotic system. Since chaotic systems are very sensitive to initial conditions, a small amount of additive noise and a slight mismatch of parameters would severely degrade the performance of communications. Synchronization of chaotic system is still an important issue, which imposes some limitations to the practical applications.

In this paper, two novel chaotic modulation methods are proposed, namely the chaotic M-ary phase shift keying (CMPSK) and chaotic M-ary frequency shift keying (CMFSK). These two methods adopt chaotic sequences to modulate parameters of carrier signal, rather than modulate parameters of chaotic signal by transmitted message bits. They don't require the exact reconstruction of the transmitted signal to drive the receiver toward synchronization. By application of chaotic sequences, the phase of CMPSK and the frequency of CMFSK behave like random noise. It's nearly impossible for unauthorized users to demodulate the signals. In order to evaluate the confidential performance of proposed chaotic modulations, we develop a feature-based automatic modulation classification (AMC) system. To achieve a high recognition rate, we adopt seven key features involving several types of representative signal processing techniques, such as instantaneous time domain [21], Fourier Transform (FT) [22], Wavelet Transform (WT) [23,24] and higher order cumulants [25]. After feature extraction, the AMC system needs a classifier to identify the type of intercepted signals. It is observed that the support vector machine (SVM) can attain higher classification rate than the Artificial Neural Networks (ANN) and the Decision Tree Approach (DT) method at a small quantity of samples [26–28]. Hence, SVM will be considered in this paper.

The remainder of this paper is organized as follows. In Section 2, the methods of chaotic modulation are given. In Section 3, we present the AMC system. Kinds of features selected are also discussed. In Section 4, simulation results between chaotic modulations and conventional digital modulations are provided to compare their confidential performances. In Section 5, an experiment was conducted to verify that chaotic modulations can achieve similar communication performance compared with conventional digital modulations in actual UWA communications. Finally, conclusions are presented in Section 6.

2. Chaotic modulations for UWA communication

A chaotic map system is one that is deterministic but appears not to be so, as a consequence of its extreme sensitivity to initial conditions. So a large number of random-like uncorrelated sequences can be generated by various chaotic map systems. Some familiar chaotic maps are Kent, Logistic-Map, Chebyshev, ICMIC maps, etc [29,30]. The improved Kent map [31] is adopted in this paper, and it is defined as

$$k_{n+1} = \begin{cases} \frac{1-(a-k_n)}{a}, & -1 \leqslant k_n < 2a-1 \\ \frac{a-k_n}{1-a}, & 2a-1 \leqslant k_n \leqslant 1 \end{cases} \tag{1}$$

In the above equation, it shows chaotic behavior when the parameter a satisfies the condition $0 < a < 1$. The values of k_n distribute randomly between -1 and 1. ($-1 \leqslant k_n \leqslant 1$). Here, we focus on simple polynomial maps that exhibit chaotic characters which can be represented using a simple non-linear dynamical equation. Besides the improved Kent map, any other chaotic maps can also be used. Since chaotic sequence is non-periodic and sensitive to initial conditions, it is quite difficult for unauthorized users to estimate it accurately from the intercepted signal with finite length. Moreover, the complexity of UWA channel adds the difficulty to parameter estimation. Next the generated chaotic sequences are applied into the two proposed modulation methods.

2.1. CMPSK modulation method

The CMPSK method modulates every original MPSK symbol with a varying additional phase determined by the corresponding element of chaotic sequence.

$$\begin{aligned} c_{cmpsk,n}(t) &= Re\left[g(t)e^{j\pi k_n}e^{j\frac{2\pi(i-1)}{M}}e^{j2\pi f_c t}\right] \\ &= g(t)\cos(2\pi f_c t + \varphi_n + \theta_n) \end{aligned} \tag{2}$$

where $g(t)$ denotes the time window for each symbol. f_c denotes the carrier frequency. $\varphi_n = \pi k_n$, $\theta_n = \frac{2\pi}{M}(i-1)$, $M = 2, 4, 8, \ldots$, $i = 1, 2, \ldots, M$, $n = 1, 2, \ldots, N$, $0 \leqslant t \leqslant T_0$, k_n is the n-th chaotic sequence, and N is the number of symbols.

In the above equation, the value of M is commonly 2, 4 or 8. CMPSK can be replaced by CBPSK, CQPSK and C8PSK when the letter 'M' is 2, 4 and 8, respectively. Without loss of generality, we take the signal of chaotic quadrature phase shift keying (CQPSK, $M = 4$) as an example here. Fig. 1 shows the modulation diagram of the CQPSK method, wherein a_n is the information symbol sequence. k_n is the chaotic sequence with a value range of $(-1, 1)$, the additional phase φ_n is defined as:

$$-1 < k_n < 1, \quad \varphi_n = \pi k_n$$

Fig. 2 shows the constellation diagrams of quadrature phase shift keying (QPSK) and CQPSK signal. It can be seen that CQPSK symbols distribute randomly on the whole unit circle which is quite different from the converging circumstance of QPSK symbols. So, without knowledge of the chaotic sequence k_n, it is nearly impossible to extract information from the CQPSK signal.

2.2. CMFSK modulation method

The conventional MFSK method represents information by making choice from M fixed carrier frequencies. So the obtained MFSK signal has typical characteristics of several separate strong spectral lines in its spectrum chart. Consequently, the modulation type and order of the MFSK signal is easy to be identified. In conclusion, the MFSK method is not proper for covert and confidential communications.

As to the CMFSK method, M carrier frequencies for choice vary with the corresponding element of a preselected chaotic sequence for every modulating symbol.

$$c_{MFSK,n}(t) = Re\left[g(t)e^{j2\pi f_n t}e^{j2\pi f_c t}\right] = g(t)\cos(2\pi f_c t + \varphi_n) \tag{3}$$