Chaotic Modulation Detection for Underwater Acoustic Communications via Instantaneous Features

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***Abstract*—Modulation detection is important for underwater military communications and warfare applications. Chaotic modulations based on chaotic sequences are proposed to protect confidential underwater communications. In this paper, we develop a detection algorithm employing instantaneous phase and frequency for underwater acoustic communications. The key features derived from instantaneous phase and frequency are used to detect two chaotic modulations. They are chaotic M-ary phase shift keying (CMPSK) and chaotic M-ary frequency shift keying (CMFSK), which are designed to provide confidential underwater communications. Simulation and experimental results confirm the effectiveness of our proposed algorithm for chaotic modulation detection.**

***Keywords*—Modulation detection, chaotic modulation, instantaneous information, underwater acoustic communications.**

I. INTRODUCTION

In underwater warfare surveillance systems, receivers should try to intercept signals and extract useful information from adversaries. The modulation detection of the intercepted signals is a key enabler to accomplish the task. Traditional digital modulation types, such as M-ary frequency shift keying (MFSK) and M-ary phase shift keying (MPSK), have been extensively applied in underwater acoustic communications. However, they are not ideal for confidential scenarios because of their well-known generating processes and signal features. On the other hand, chaotic sequences contain random information which is nonlinear and sensitive to the initial value. Therefore, modulated signals based on chaotic sequences are not easy to be distinguished and suitable for confidential communications. Two novel chaotic modulation methods based on chaotic sequences, namely chaotic M-ary phase shift keying (CMPSK) and chaotic M-ary frequency shift keying (CMFSK), are proposed to provide confidential underwater communications [1]. These two methods adopt chaotic sequences to modulate parameters of carrier signals, such as the frequency and phase. To counter their confidentiality and extract the information, the detection of the type of the chaotic modulation is a primary requirement.

Feature-based (FB) and likelihood-based (LB) methods [2] are applied in modulation detection. The LB methods have two steps: i) calculate the likelihood function of the received signal for all candidate modulations, and ii) use the maximum likelihood ratio to set thresholds in order to differentiate the modulation type. In the FB algorithms, several features are extracted from the received signal and then applied to a classifier in order to distinguish the modulation types. Furthermore, cyclostationary analysis is a kind of the FB methods. It is applied to detect underwater acoustic signals based on the second order cyclostationary features [3][4]. However, the algorithms in [3][4] based on the second order cyclostationary features cannot further distinguish the modulation schemes between quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM). An LB algorithm is applied to further distinguish between QPSK and 16QAM modulation in underwater acoustic communications [5]. Though it suffers from expensive computational complexity. Further, the algorithms above cannot detect the chaotic-type modulations. Nevertheless, instantaneous feature-based (IFB) methods [6][7] are another essential tool in modulation detection. They are also a kind of FB methods. In the IFB approaches, instantaneous features, such as instantaneous amplitude, frequency and phase, are extracted from the intercepted signal and then applied to a classifier in order to recognize the modulation type. Although the IFB methods may not be optimal, they are simple to implement. When they are designed properly, the performance is near-optimal.

In this paper, we propose a modulation detection scheme for underwater acoustic signals through three key features using the IFB method. The key features proposed for the detection algorithm are derived from the instantaneous phase and frequency of the received signal. We use the instantaneous key features to detect the chaotic-type modulations, including CMPSK and CMFSK. The classifier is designed to first discriminate MPSK and CMPSK signals from MFSK and CMFSK signals, and further differentiate the specific modulations. Simulations and experiments in underwater environments confirm the effectiveness of the proposed method.

The rest of the paper is organized as follows. In Section II, we describe the signal model of the chaotic modulations

978-1-5090-1537-5/16/$31.00 ©2016 IEEE

which are proposed to provide confidential underwater communications. In Section III, we introduce the estimation of instantaneous features using the IFB method and develop a modulation detection scheme. Section IV shows results of the chaotic modulation detection for underwater acoustic communications in simulations and experiments respectively. Conclusions are drawn in Section V.

II. The signal model of the chaotic modulations

CMPSK and CMFSK methods are proposed to provide confidential communications. They modify MPSK and MFSK by adding the information of chaotic sequences. The improved kent map [8], one of the typical chaotic maps, is used to generate chaotic sequences and defined as follows.

$$k_{i+1} = \begin{cases} \dfrac{1-(a-k_i)}{a} & -1 \le k_i < 2a-1 \\ \dfrac{a-k_i}{1-a} & 2a-1 \le k_i \le 1 \end{cases}, \quad 0 < a < 1, \tag{1}$$

where the parameter a satisfies the condition $(0 < a < 1)$, the value of k_i meets the condition $(-1 \le k_i \le 1)$, and k_i represents the i-th element in the chaotic sequence.

The CMPSK signal [1] modulates every original MPSK symbol with a varying additional phase determined by the corresponding element of the chaotic sequence as follows.

$$c_{cmpsk}(t) = \sum\nolimits_i g(t-iT)\cos(\omega_c t + \theta_i)\ , \tag{2}$$

where $g(t-iT)$ is the time window for each symbol with T the symbol interval. The parameter $\omega_c = 2\pi f_c$, where f_c denotes the carrier frequency. The parameter $\theta_i = \frac{2\pi}{M}(a_i - 1) + \pi k_i$, where M is the modulation order ($M \in \{2, 4, ...\}$), and a_i is the data symbol ($a_i \in \{1, 2, ..., M\}$). The symbol index is represented by i. The additional phase πk_i is the chaotic sequence. The value of M is usually 2 or 4. Hence, CMPSK can be replaced by C2PSK or C4PSK, when M is 2 or 4.

For the CMFSK signal [1], M frequencies vary with the corresponding element of a preselected chaotic sequence for every symbol. The CMFSK signal is given by

$$c_{cmfsk}(t) = \sum\nolimits_i g(t-iT)\cos(\omega_c t + 2\pi f_i t), \tag{3}$$

where $f_i = k_i \Delta f - sign(k_i) b_i \Delta f$, representing the frequency added to the carrier frequency. The function of $sign(x)$ can be defined as $sign(x) = \begin{cases} 1 & x \ge 0 \\ -1 & x < 0 \end{cases}$. The parameter Δf is the frequency interval. The data symbol $b_i \in \{-M/2+1, ..., -1, 0, 1, 2, ..., M/2\}$. Similarly as the CMPSK method, $M \in \{2, 4, ...\}$. CMFSK can also be replaced by C2FSK or C4FSK when M is 2 or 4. For instance, for C2FSK signal, the modulation frequency can be calculated by

$$f_i = \begin{cases} k_i \Delta f & b_i = 0 \\ k_i \Delta f - sign(k_i)\Delta f & b_i = 1 \end{cases}.$$

III. Estimation of instantaneous features and Modulation detection method

A. Estimation of instantaneous features

The modulated underwater acoustic signals are transmitted and experience the underwater acoustic channel. Therefore, the received signals can be denoted as

$$x(t) = c(t) \otimes h(t) + n(t)\,, \tag{4}$$

where $c(t)$ stands for the transmitted signals, such as $c_{cmpsk}(t)$ or $c_{cmfsk}(t)$, $\otimes$ represents the convolution, $h(t)$ is the model of underwater acoustic channel and $n(t)$ corresponds to the additive white Gaussian noise (AWGN).

When the receiver intercepts the underwater acoustic signal, we can extract its instantaneous frequency and phase, and use them to determine the modulation type among MFSK, MPSK, CMFSK and CMPSK. The received signal $x(t)$ is sampled as $x[n]$, and can be represented as the analytic signal $z[n]$ by taking a Hilbert transform [6], where n is the n-th sample point of the intercepted signal. The analytic signal $z[n]$ is expressed as

$$z[n] = x[n] + jy[n]\,, \tag{5}$$

where $y[n]$ is the Hilbert transform of $x[n]$, and j is the imaginary unit. From the analytic signal, we can calculate the instantaneous phase $\phi[n]$ and frequency $f[n]$. As a result, the instantaneous phase is given by

$$\phi[n] = \arctan\left(\frac{y[n]}{x[n]}\right)\ . \tag{6}$$

The instantaneous frequency is given by

$$f[n] = \frac{\phi[n] - \phi[n-1]}{\Delta t}\ , \tag{7}$$

where $\Delta t = 1/f_s$ is the sampling interval, and f_s is the sampling rate.

Based on the above instantaneous phase and frequency, three key features are defined. The first key feature, M_{f1}, is proposed to represent the average of the absolute value of the normalized-centered instantaneous frequencies. The second feature, M_{f2} , is the standard deviation of the absolute value of the normalized-centered instantaneous frequencies [6][7]. First, we define

$$\begin{gathered} \mu_f = \frac{1}{N}\sum_{n=1}^{N} f[n], \\ f_d[n] = f[n] - \mu_f, \\ r_f[n] = 2f_d[n]/B\ , \end{gathered} \tag{8}$$

where B is the bandwidth of the signal, and μ_f is the average of the instantaneous frequencies for all of the samples. Sequentially, we arrive at

$$M_{f1} = \frac{1}{N}\sum_{n=1}^{N} |f_d[n]/\mu_f|, \tag{9}$$

$$M_{f2} = \sqrt{\frac{1}{N}\left(\sum_{n=1}^{N} r_f^2[n]\right) - \left(\frac{1}{N}\sum_{n=1}^{N} |r_f[n]|\right)^2}. \tag{10}$$

The third key feature, M_p, is the standard deviation of the absolute value of the non-linear component of the normalized-centered instantaneous phases [6][7]. Let us define

$$\begin{aligned} \phi_d[n] &= \phi[n] - 2\pi f_c n / f_s, \\ r_\phi[n] &= \frac{\phi_d[n]}{\frac{1}{N}\sum_{n=1}^{N}\phi_d[n]} - 1, \end{aligned} \tag{11}$$

where $\phi_d[n]$ is the non-linear component of the instantaneous phase. The third key feature M_p is given by

$$M_p = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{N} r_\phi^2[n]\right) - \left(\frac{1}{N}\sum_{i=1}^{N}|r_\phi[n]|\right)^2}. \tag{12}$$

The choices of M_{f1}, M_{f2} and M_p as key features are based on the following facts:

1) M_{f1}: MPSK and CMPSK signals have constant frequency, thus the instantaneous frequencies of the intercepted signals remain unchanged. Their M_{f1} value is zero. However, MFSK and CMFSK do not have constant instantaneous frequencies. Hence, their normalized-centered instantaneous frequencies possess frequency information and their M_{f1} must be greater than zero. Therefore, M_{f1} is used to discriminate MPSK and CMPSK signals from MFSK and CMFSK signals.

2) M_{f2}: MFSK signals have M different modulation frequencies. That is to say, 2FSK signals have two different modulation frequencies and 4FSK signals have four. Although CMFSK also have M different modulation frequencies for each symbol, the M frequencies vary according to the generated chaotic sequences. The different values of instantaneous frequencies of the intercepted signals lead to the different values of the normalized-centered instantaneous frequencies. Thus, 2FSK, 4FSK, C2FSK and C4FSK signals have different M_{f2} values. Therefore, we can set thresholds, use M_{f2} to discriminate MFSK and CMFSK signals, and recognize the modulation order of the signal.

3) M_p: Similarly as the analysis of M_{f2}, MPSK signals have M different modulation phases which are removed the linear component. That is to say, 2PSK signals have two different modulation phases 0 and π, and 4PSK signals have four, 0, $\frac{\pi}{2}$, π and $\frac{3}{2}\pi$. Although CMPSK also have M different modulation phases for each symbol, the values of the M phases are not fixed and they vary according to the generated chaotic sequences. The different values of instantaneous phases of the intercepted signals lead to the different values of the non-linear component of the normalized-centered instantaneous phases. Thus, MPSK and CMPSK signals have different M_p values. Therefore, we can set thresholds, use M_p to discriminate MPSK and CMPSK signals, and recognize the modulation order.

B. Modulation detection method

Based on the three key features, we propose a hierarchical algorithm to classify the modulation type of underwater acoustic communication signals including chaotic-type modulations. We focus on the modulation classification among MFSK, CMFSK, MPSK and CMPSK. Fig. 1 shows the proposed hierarchical modulation classification scheme. It involves two steps. A short frame of the received signal is fed to the hierarchical modulation classifier.

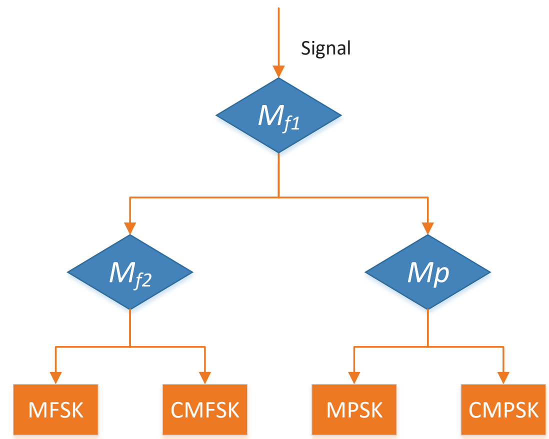

Fig. 1. A hierarchical classifier for modulation detection

Step 1: M_{f1} feature is exploited to distinguish MFSK and CMFSK modulations from MPSK and CMPSK modulations.

Step 2: If the signal is identified as MFSK or CMFSK modulation, a M_{f2} key feature detection is applied to further distinguish between MFSK and CMFSK modulation and recognize its modulation order. Similarly, after *Step 1*, if the signal is identified as MPSK or CMPSK modulation, a M_p key feature detection is exploited to discriminate MPSK and CMPSK modulation and recognize its modulation order.

IV. Results

A. Simulation Results

We carry out a simulation to acquire three key features vs. SNR curves. Figs.2-4 show the resulting plots for each modulation signal for the number of the samples $N = 7200$, the sampling rate $f_s = 96\,\text{kHz}$, the carrier frequency $f_c = 20\,\text{kHz}$, the symbol rate $1/T = 4\,\text{kHz}$, and the bandwidth $B = 8\,\text{kHz}$ for MFSK and CMFSK signals.

According to Figs.2-4, we can set thresholds of the three key features of the modulation detection algorithm to detect the modulation scheme hierarchically. After setting the thresholds of the three key features, each signal for different modulation scheme experiences the AWGN channel and the SNR value of 20 dB. We test 10000 groups of received signals from different modulations and Table I shows the probability of detection of the received signals. Further, each signal experiences the Bellhop [9] underwater acoustic channel with three-path and the SNR value of 20 dB. We also test 10000 groups of received signals from different modulations and Table II shows the probabilities of detection.

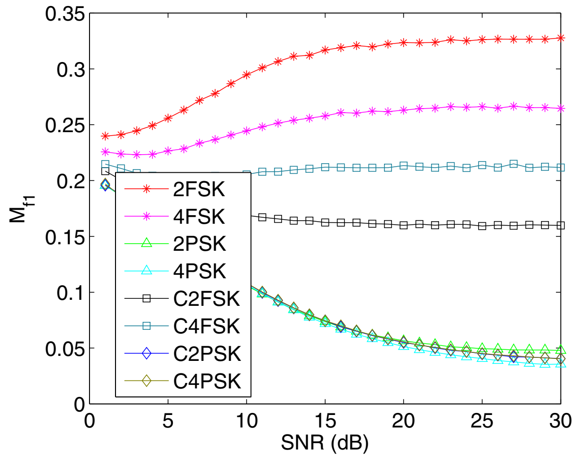

Fig. 2. Dependence of M_{f1} on SNR

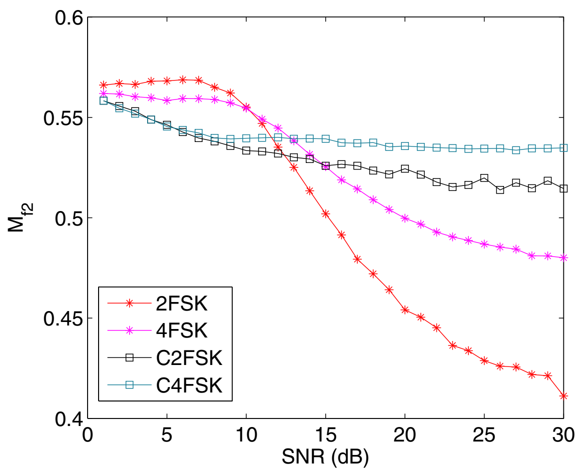

Fig. 3. Dependence of M_{f2} on SNR

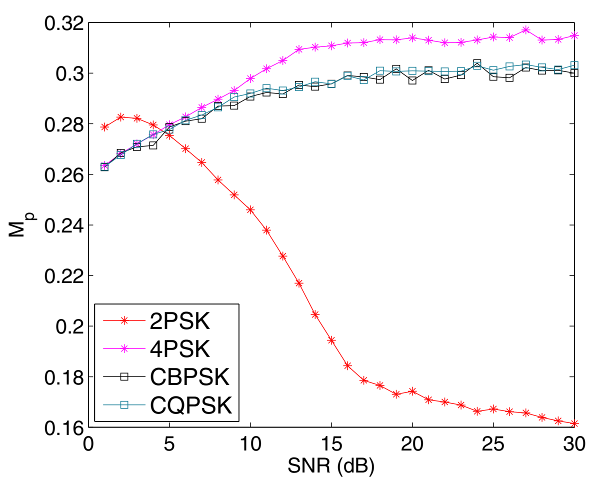

Fig. 4. Dependence of M_p on SNR

In the simulation, we can detect chaotic modulation. However, for CMPSK modulation, we can detect but cannot recognize its modulation order. The reason why is that the additional phases of C2PSK and C4PSK signals are random and are not distinguishable. Moreover, other modulations have high probabilities of detection. The probabilities of detection for each modulation through AWGN channel are higher than through the Bell-hop underwater acoustic channel with multi-path. That implies the complex multipath of underwater acoustic channel will affect the accuracy of the modulation detection.

TABLE I
MODULATION DETECTION IN AWGN CHANNEL WITH SNR = 20 dB

Signal Type	2FSK	4FSK	C2FSK	C4FSK
Probability of Detection	100%	85.6%	81.3%	96.5%
Signal Type	2PSK	4PSK	CMPSK	
Probability of Detection	89.9%	96.3%	99.9%	

TABLE II
MODULATION DETECTION IN BELL-HOP UNDERWATER ACOUSTIC CHANNEL WITH THREE-PATH AND SNR = 20 dB

Signal Type	2FSK	4FSK	C2FSK	C4FSK
Probability of Detection	99.9%	74.3%	61.0%	96.7%
Signal Type	2PSK	4PSK	CMPSK	
Probability of Detection	84.9%	93.2%	96.6%	

TABLE III
MODULATION DETECTION IN SI-YUAN LAKE

Signal Type	2FSK	4FSK	C2FSK	C4FSK
Probability of Detection	72%	56%	65%	73%
Signal Type	2PSK	4PSK	CMPSK	
Probability of Detection	63%	68%	71%	

B. Experimental Results

To verify the modulation detection performance of the proposed algorithm, we carry out experiments in Si-Yuan Lake, in Shanghai Jiao Tong University campus. Two underwater acoustic modems from AquaSeNT [10] were deployed underwater. Figs.5-6 show the underwater acoustic modem and experiment scene. One modem transmits eight different modulation-type signals, and the other one receives them. The distance between two modems is 70 m. The transmitted signals have the same parameters as the ones in the simulations. The transmit power is set as 1.067 W. We sent each modulation-type signal 10 times. For one group signal, we truncated into 10 segments. The length of the segment is 10000 samples. Therefore, in the experiments, there are 100 segments for each modulation-type to be tested by the modulation detection algorithm. Table III shows the probabilities of detection. Although, there are not huge amounts of segments, we can still detect chaotic-modulation type. However, the correct probabilities of detection is not as good as that in simulations because of the real and complex underwater environments.

V. CONCLUSIONS

In this paper, we have employed three key features based on instantaneous frequency and phase to detect modulation

Fig. 5. Acoustic modem

Fig. 6. Experiment scene

types including chaotic modulations, which are used for underwater acoustic confidential communications. Simulations over AWGN and Bell-hop underwater acoustic channels confirm the effectiveness of the proposed detection algorithm. Moreover, experiments were conducted with underwater acoustic modems to detect our scheme, and the results also validate the effectiveness of the proposed method.

Acknowledgment

Part of this work was supported by the National Nature Science Foundation of China under the grants 61471237 and 61301223, the Research Found for the Doctoral Program of Higher Education under 20130073120055, and Shanghai Economic and Information Commission under CXY-2014-007.

References

[1] X. Shu, H. Wang, X. Yang and J. Wang, "Chaotic modulations and performance analysis for digital underwater acoustic communications," *Applied Acoustics*, vol. 105, pp. 200-208, 2016.

[2] O.A. Dobre, A. Abdi, Y. Bar-Ness and W. Su, "Survey of automatic modulation classification techniques: classical approaches and new trends," *IET Communications*, vol.1, pp.137-156, 2007.

[3] Z. Wu, T. C. Yang, Z. Liu and V. Chakarvarthy, "Modulation detection of underwater acoustic communication signals through cyclostationary analysis," in *Proc. IEEE MILCOM*, Orlando, FL, pp. 1-6, 2012.

[4] X. Li, Q. Han, Z. Liu and Z. Wu, "Novel modulation detection scheme for underwater acoustic communication signal through short-time detailed cyclostationary features," in *Proc. IEEE WCNC*, Istanbul, pp. 624-629, 2014.

[5] J. Sanderson, X. Li, Z. Liu and Z. Wu, "Hierarchical blind modulation classification for underwater acoustic communication signal via cyclostationary and maximal likelihood analysis," in *Proc. IEEE MILCOM*, San Diego, CA, pp. 29-34, 2013.

[6] E. Moser, M. K. Moran, E. Hillen, D. Li and Z. Wu, "Automatic modulation classification via instantaneous features," in *Proc. IEEE NAECON*, Dayton, OH, pp. 218-223, 2015.

[7] E. Azzouz and A. Nandi, "Automatic identification of digital modulation types," *Signal Processing*, vol. 47, pp. 55-69, 1995.

[8] H. Wang, L. Wu, "Long range underwater acoustic communication basedon chaotic-FM M-ary mode," *ACTA ACOUSTIC*, vol. 29, pp. 161-166, 2004.

[9] M. Porter *et al.*, "Bellhop code," [Online]. Available: http://oalib.hlsresearch.com/Rays/index.html

[10] AquaSeNT, Acoustic modems, http://www.aquasent.com/.