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Extraction of periodic signals in chaotic secure communication using Duffing oscillators*

Wang Yun-Cai(王云才)†, Zhao Qing-Chun(赵清春), and Wang An-Bang(王安帮)

Department of Physics, College of Science, Taiyuan University of Technology, Taiyuan 030024, *China*

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This paper presents a novel approach to extract the periodic signals masked by a chaotic carrier. It verifies that the driven Duffing oscillator is immune to the chaotic carrier and sensitive to certain periodic signals. A preliminary detection scenario illustrates that the frequency and amplitude of the hidden sine wave signal can be extracted from the chaotic carrier by numerical simulation. The obtained results indicate that the hidden messages in chaotic secure communication can be eavesdropped utilizing Duffing oscillators.

Keywords: chaos, signal extraction, Duffing oscillator, secure communication
PACC: 0545

1. Introduction

Data security is one of the most important issues in communication systems. Since Pecora and Carroll first introduced[1] the idea of chaos synchronization, many researches have been undertaken aiming at achieving chaotic secure communication.[2−7] In chaotic secure communication system, the messages are hidden in a chaotic carrier generated by a transmitter, and recovered by a synchronized chaotic receiver after transmission. The chaotic receiver, can be viewed as a nonlinear filter, generates locally a message-free chaotic signal which is used for subtraction from the encoded transmitted signal. In this communication system, the encoded signal is generated at the physical layer (hardware encryption) instead of the algorithmic encryption (software encryption). Thus it is stated that an eavesdropper can not unmask the hidden messages without any knowledge of the transmitter parameters in advance. However, the investigation of the security performance of chaotic communication in recent years has shown that eavesdropping on the hidden messages can be implemented by dynamical reconstruction of the chaotic transmitter using nonlinear dynamical forecasting (NLDF), simple return maps,[8,9] and so on.[10,11] The NLDF methods mainly include Stark prediction,[12] nonlinear inverse of linear filter,[13] and neural network,[14] etc. The disadvantages of NLDF methods are the complicated processes. The method of signal extraction utilizing the return maps technique is simple, but it is not suitable for high frequency signal extraction.

In this paper, a simple scheme for extraction messages masked by a chaotic carrier is proposed, and a sine wave signal hidden in the chaotic carrier, which is generated by the conventional Lorenz chaotic circuit, is illustrated by numerical simulation. We demonstrate that the driven Duffing oscillator is immune to the Lorenz chaotic carrier and sensitive to the sine wave signal according to Refs.[15–17]. The advantages of this method are that the process is simple for extraction a sine wave signal masked by the chaotic carrier and the setup is convenient for practical applications.

2. Principle

The setup for extracting signals masked by a chaotic carrier is shown in Fig.1. The left block (in dotted line) of the setup is used to extract the frequency of the signal. The approximate frequency range of the transmitted signal is obtained from the spectrum analyser. Then, the frequency of the signal is scanned by changing the inner frequency of the driving force of Duffing oscillator 1 with an equal-ratio of 1.03 until intermittent chaos is observed on oscilloscope 1 (OSC1). By calculating the period of the intermittent chaos, we can obtain the unknown fre-

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†E-mail: wangyc@tyut.edu.cn

quency. The right block of Fig.1 is utilized to extract the amplitude of the signal. After being passed through an amplifier whose magnification times is set to 10^n $(n = \cdots, -2, -1, 0, 1, 2, \cdots)$, the amplitude of the transmitted signal is adjusted to a suitable range, e.g. from 0.001 to 0.01, which is considered to be a weak signal in comparison with the Duffing oscillator. The amplitude of the signal can be obtained on oscilloscope 2 (OSC 2) by adjusting the driving force item of Duffing oscillator 2.

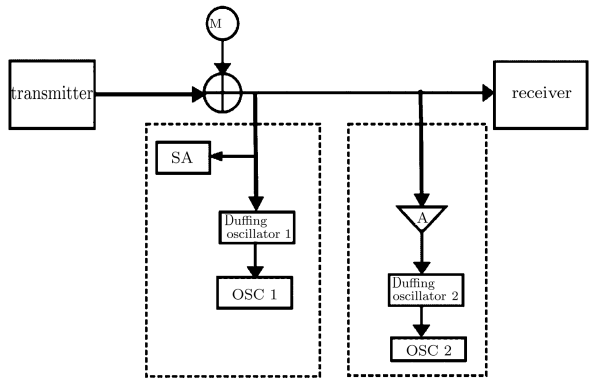


Fig.1. Block diagram for extraction signals masked by the chaotic carrier. SA: spectrum analyser; OSC: oscilloscope; A: amplifier.

Here, we use the typical Lorenz system as the chaotic transmitter, which is described as follows:

$$\begin{aligned} \frac{\mathrm{d}u}{\mathrm{d}t} &= \sigma\,(v-u)\,, \\ \frac{\mathrm{d}v}{\mathrm{d}t} &= ru - v - 20u\omega, \\ \frac{\mathrm{d}\omega}{\mathrm{d}t} &= 5uv - b\omega \end{aligned} \tag{1}$$

with the parameters

$$\sigma = 16, \quad b = 4, \quad r = 45.92.$$

The analogic signal is supposed to be $m(t) = a\cos(\omega t)$ with $a = 0.5$ and $\omega = 5\,\mathrm{rad/s}$, which is added outside the transmitter to the chaotic carrier $u(t)$ and masked by it (see Fig.2).

The Duffing oscillator is expressed by the following equations:

$$\begin{aligned} \frac{\mathrm{d}x}{\mathrm{d}t} &= \omega_0 y, \\ \frac{\mathrm{d}y}{\mathrm{d}t} &= \omega_0\left(-\delta y + x - x^3 + \gamma\cos\left(\omega_0 t\right) + \mathrm{input}\right), \end{aligned} \tag{2}$$

where δ is the damping ratio fixed to 0.5 and $\gamma\cos(\omega_0 t)$ is the driving force.

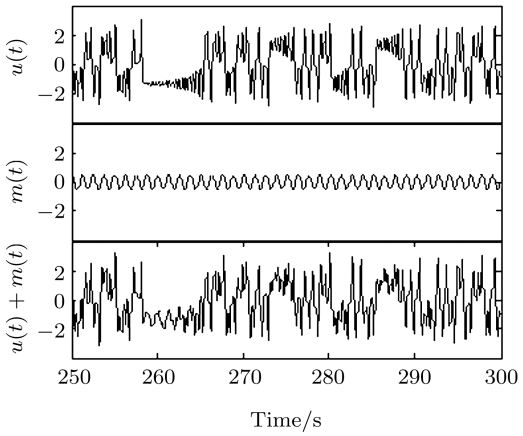


Fig.2. Time series of the chaotic carrier $u(t)$, the hidden signal $m(t)$, and the transmitted signal $u(t) + m(t)$.

We numerically solve Eq.(2) and plot the phase portraits of $x(t)$ and $y(t)$ in Fig.3 when the 'input' is set to 0, $0.01u(t)$, $0.005\cos(5t)$, $0.01u(t)+0.005\cos(5t)$, separately. The Duffing oscillator undergoes chaotic state when the driving force is $0.822\cos(5t)$ presented in Fig.3(a). Then the chaotic carrier is added to the 'input' and the magnification times of the amplifier is set to 0.01, which shows that it only induce the local effect on the oscillator. After being added a periodic signal whose frequency is the same as that of the driving force, the phase transition of the oscillator occurs immediately and the regular great periodic motion can be observed. Figure 3(d) shows the results when the chaotic carrier is added to the input signal which is shown in Fig.3(c). The thicker phase portrait also indicates the immunity of the oscillator to the chaotic carrier.

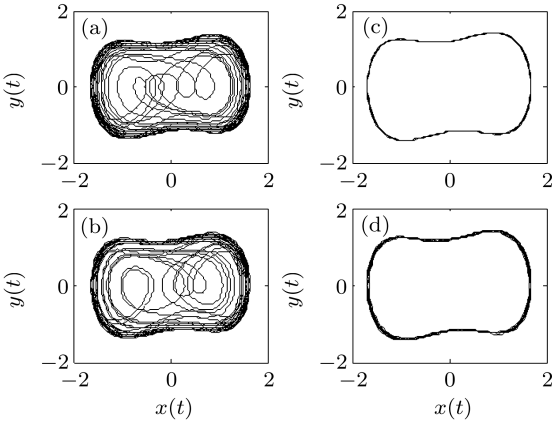


Fig.3. Phase portraits of the Duffing oscillator: (a) driven by the outside periodic force $0.822\cos(5t)$; (b) driven by the outside periodic force and the chaotic carrier $0.01u(t)$; (c) driven by the outside periodic force and the periodic signal $0.005\cos(5t)$; (d) driven by the above three signals.

From the above analysis, we conclude that although the chaotic carrier may be intense, it only causes local effect on the Duffing oscillator; while the periodic signal whose frequency is the same as that of the driving force can arouse phase transition even if it is weak. This property is used to extract a sine wave signal masked by the chaotic carrier generated by the Lorenz transmitter, as demonstrated in the next section.

3. Detection procedures

Let the transmitted signal $s(t)$ pass the detector. The Duffing oscillator 1, the initial frequency of the driving force is 1 rad/s, exhibits intermittent chaos when the frequency is set to $\omega_{55} = 4.9341$ rad/s and $\omega_{56} = 5.0821$ rad/s, separately. In Figs.4(b) and 4(d), we note that the oscillator undergoes intermittent chaos including great periodic motion. The cycle time of the intermittent chaos in Figs.4(a) and 4(c) is 100 s and 180 s, respectively. So the corresponding frequency difference is $\Delta\omega_{55} = 2\,\pi/T_{55} = 0.0628$ rad/s and $\Delta\omega_{56} = 2\,\pi/T_{56} = 0.0349$ rad/s. Now the frequency of the signal is

$$\begin{aligned}\omega' &= (\omega_{55} + \Delta\omega_{55} + \omega_{56-}\Delta\omega_{56})/2 \\ &= 5.0221\,\text{rad/s}. \end{aligned} \tag{3}$$

Hence, the relative error is 0.44%.

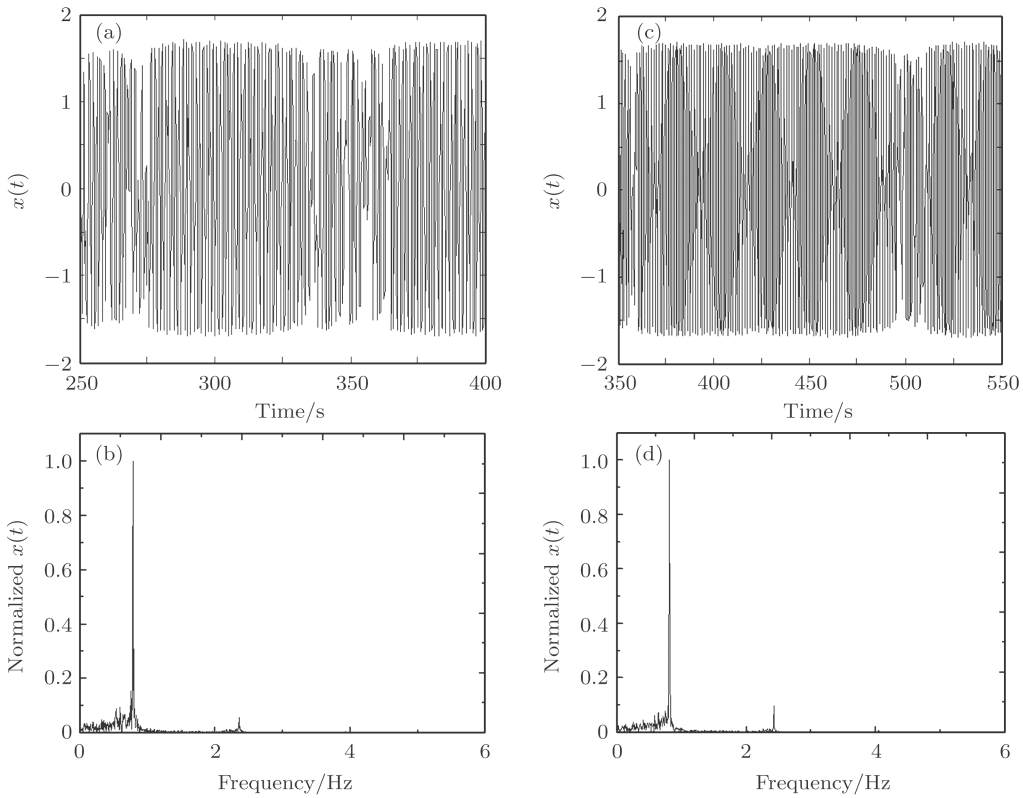


Fig.4. Time series and normalized spectrum of $x(t)$ after adding the transmitted signal $s(t)$. The frequency of the driving force is 4.9341 rad/s and 5.0821 rad/s, respectively.

If only periodic motion is observed on the time series, it will indicate that the frequency of the signal equals to that of the driving force.

The critical amplitude (which is the corresponding state of the oscillator from chaos to periodic motion) of the driving force is $\gamma_c = 0.828$ when the frequency of the driving force is set to 5.0221 rad/s. After being passed through the amplifier whose magnification times is 0.01, the transmitted signal is sent to the Duffing oscillator 2 whose frequency of the driving force is the same as that of the signal. By changing the amplitude of the driving force with a step size of 0.001, we obtain the measured amplitude of the signal

$$\begin{aligned}a' &= 10^{-n}(\gamma_c - \gamma_c') = 100 \times (0.828 - 0.823) \\ &= 0.5, \end{aligned} \tag{4}$$

where γ_c' is the critical amplitude of the driving force after adding the transmitted signal.

With these two steps, we finally obtain the hidden signal

$$m'(t) = a' \cos(\omega' t) = 0.5 \cos(5.0221t), \tag{5}$$

as shown in Fig.5. The corresponding signal to chaos ratio (SCR) is

$$\begin{aligned} \text{SCR} &= 10 \ \lg \left(\frac{\text{signal power}}{\text{chaotic carrier power}} \right) \\ &\approx -11 \, \text{dB}. \end{aligned} \tag{6}$$

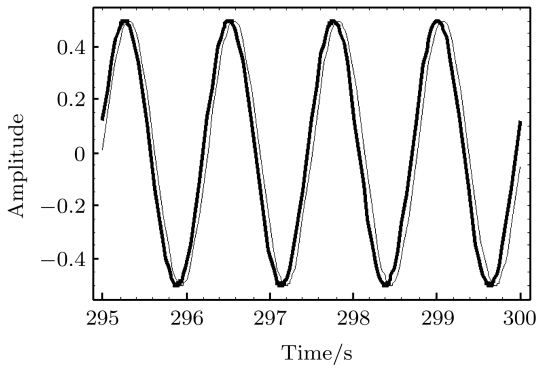


Fig.5. The extracted signal. The thin line is the original signal while the thick line is the extracted signal.

4. Discussions

The phase of the hidden sine wave signal may be extracted by using the reverse-phase-compensation-amplitude-estimation method or the trisection-symmetry-phase-estimation method.[18] This issue will be investigated in the future work. By using frequency scanning, we can extract more than one added sine wave signal with the same function and different parameters, e.g. $a_1\cos(\omega_1 t) + a_2\cos(\omega_2 t) + \cdots + a_n\cos(\omega_n t)$. The approach to extract signals masked by the chaotic carrier generated by the Lorenz system can also be applied to other types of chaotic transmitters, such as the hyperchaotic Rössler system.[19] This method is helpful to eavesdrop on real voice and radio messages masked in chaotic secure communication.

5. Conclusions

In summary, we have shown a novel method for extraction signals masked by a chaotic carrier based on Duffing oscillators. We have demonstrated this method by using a typical example in the Lorenz chaotic masking communication. The system configuration is presented and the numerical simulation results are illustrated. This simple message extraction technique can be applied in practice more easily in comparison with these current methods for extraction signals masked by a chaotic carrier. The advantage of this method is that only two steps are needed to extract a sine wave signal masked in chaos instead of complex calculations. We have also pointed out its application in other chaotic secure communication systems.

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