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On an aperiodic stochastic resonance signal processor and its application in digital watermarking

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Abstract

In this paper, an aperiodic stochastic resonance (ASR) signal processor for communication systems based on a bistable dynamic mechanism is proposed for detecting base-band binary pulse amplitude modulation (PAM) signals in communication systems. All parameters in the processor can be adjusted when needed. The adjustment mechanism is explained from the perspective of the conventional noise-induced nonlinear signal processing. To demonstrate this processor's usability, a digital image-watermarking algorithm in the discrete cosine transform (DCT) domain is implemented. In this algorithm, the watermark and the DCT alternating current (ac) coefficients of the image are viewed as the input signal and the channel noise, respectively. In conventional watermarking systems, it is difficult to explain why the detection bit error ratio (BER) of a watermarking system suffering from certain attacks is lower than that of the system not suffering from any attack. In the new watermarking algorithm, this phenomenon is systematically analyzed. It is shown that the DCT ac coefficients of an image as well as the noise imposed by the attacks can cooperate within the bistable system to improve the performance of the watermark detection.

Keywords: Signal processing; Aperiodic stochastic resonance; Digital watermarking

1. Introduction

The stochastic resonance (SR) effect has been observed in many nonlinear systems, such as in climatic dynamics [1], electronic circuit [2], capacity of particular nonlinear channel [3], among others. From the signal-processing perspective, the SR effect is commonly understood as an increase followed by a decrease in the signal-to-noise ratio (SNR) at the output with a continuously increasing noise level at the input. Other quantitative measures, such as the bit error ratio (BER) used in the current study, can also be employed. More detailed information about SR can be found in Refs. [4–7]. SR is an effective approach for signal processing. It can be used in detecting periodic signals, such as sinusoids in Refs. [8,9]. This kind of SR is referred to as conventional SR. It can also be used in

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detecting aperiodic signals, such as the base-band binary pulse amplitude modulation (PAM) signals in Refs. [3,11,12]. This kind of SR is referred to as aperiodic stochastic resonance (ASR) [10].

A pioneering study on ASR for transmitting an arbitrary fixed-length binary input sequence was done by Hu et al. [11]. In that study, a bistable dynamic system driven by an aperiodic signal and noise was proposed. Under the SR condition, the portion of the information received by the bistable system can be greatly enhanced. Evaluation of the input–output information capacity was then carried out by Godivier and Chapeau-Blondeau [3]. The phenomenon of increase in channel capacity by means of certain noise injection was interpreted as another form of SR.

In most communication systems, however, the noise is usually a property of the channel and therefore cannot be adjusted by the receiver and neither by the sender. In this case, it is more practical to tune the parameters of the system [13–17] for the best performance. Two methods of realizing ASR by adding certain amount of noise and tuning system parameters in the bistable system were compared in a real parameter space [18]. The results showed that adding noise could be treated as a special case of tuning system parameters. Further, the method of tuning system parameters takes the precedence of the approach of adding noise for an adjustable bistable system. An experimental method was proposed to tune the bistable system for its best performance that minimized its detection error [19]. However, an important issue that has not yet been fully explored is how to tune the parameters of a system to obtain a practical ASR signal processor for a given communication condition to take advantage of the noise.

In this paper, a signal processor, named ASR signal processor, based on the aforementioned bistable system is investigated. We propose a method to improve the performance of the whole system by adjusting the parameters of the ASR signal processor. The mechanism of this method will be explained from the perspective of the conventional noise-induced nonlinear signal processor. To demonstrate its usability, we implement a digital image-watermarking algorithm in the discrete cosine transform (DCT) domain based on this ASR signal processor. By doing so, the watermark detection performance is improved.

The paper is organized as follows. In the next section, a signal processor based on a nonlinear bistable system is investigated, together with the method to design it. A digital image-watermarking algorithm in DCT domain is then implemented based on this ASR signal processor in Section 3. Experimental results are presented in Section 4 and conclusions are drawn in Section 5.

2. A bistable ASR signal processor and its design

2.1. A bistable ASR signal processor

From the signal processing perspective, the mathematical model of a nonlinear bistable dynamic system can be written as:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \frac{-\mathrm{d}V(x)}{\mathrm{d}x} + \mathrm{Input}(t), \tag{1}$$

where $V(x)$ is a quartic potential function and can be written as $V(x) = -ax^2/2 + \mu x^4/4$. The parameters a and μ are positive and given in terms of the potential parameters. The quartic potential function $V(x)$ represents a bistable nonlinear potential with two wells and a barrier. The two wells of the potential are located at $x = \pm x_{\mathrm{m}}$ with $x_{\mathrm{m}} = \sqrt{a/\mu}$ and the height of the barrier ΔV is $a^2/4\mu$. The input can be written as $\mathrm{Input}(t) = h(t) + \xi(t)$, where $h(t)$ is the input signal and $\xi(t)$ is the noise. If the signal $h(t)$ is an aperiodic signal and the SR effect occurs, it is called an ASR system [10].

This bistable system was used by Hu et al. [11], Godivier and Chapeau-Blondeau [3] and Duan and Xu [12] to detect the base-band PAM aperiodic binary signal $h(t)$ in the presence of the channel noise $\xi(t)$, as shown in Fig. 1. The signal waveforms can be expressed as $h_1(t) = -A$ and $h_2(t) = A$ for $(n-1)T_{\mathrm{s}} \leqslant t < nT_{\mathrm{s}}$, $n = 1,2, \ldots$. If the amplitude of the aperiodic signal A is not larger than the critical value $A_{\mathrm{CR}} = \sqrt{4a^3/27\mu}$ [20], the input signal is referred as sub-threshold signal and supra-threshold signal otherwise. There is a new form of ASR, i.e., residual ASR phenomenon, surviving in slightly supra-threshold optimal systems [18,21]. The current study is limited to the sub-threshold system, i.e., $A < A_{\mathrm{CR}}$. Here, a parameter Q_{SR} called

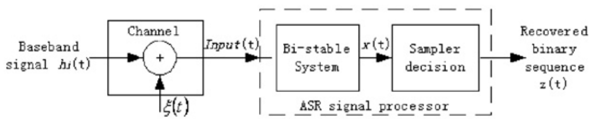

Fig. 1. ASR signal processor in a base-band binary communication system.