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Enhanced coding for exponentially distributed signals using suprathreshold stochastic resonance

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Abstract

Our previous work on stochastic resonance (SR) in threshold based systems proved that the SR effect is dependent on the nature of the input signal distribution; more specifically, for certain types of signal distribution SR is not observed [Das A, Stocks NG, Nikitin A, Hines EL. Quantifying stochastic resonance in a single threshold detector for random aperiodic signals. Fluctuation Noise Lett 2004;4:L247–65]. Here we show that suprathreshold stochastic resonance (SSR) – a novel and distinct form of SR – removes this limitation and hence leads to the conclusion that SSR can probably enhance the transmission of signals of any distribution and amplitude. SSR effects are studied in a parallel array of identical nonlinear threshold based devices. A double exponential signal distribution is chosen because this distribution did not demonstrate conventional SR effects in a single threshold device [Das A, Stocks NG, Nikitin A., Hines EL. Quantifying Stochastic resonance in a single threshold detector for random aperiodic signals. Fluctuation and Noise Letters 2004;4:L247-L265.]. SSR as a possible mechanism for enhancing transmission of speech signals in the human ear is also discussed.

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1. Introduction

Noise is usually considered to be a nuisance, degrading the performance of systems. But in nonlinear systems that display stochastic resonance (SR), the presence of noise offers the potential to enhance the transmission of weak signals. SR is the enhancement, by noise, of the response of a system to a weak signal. Most occurrences of SR known today involve a signal which is smaller than the threshold level – the addition of noise makes the signal cross the threshold giving rise to an enhanced response. The study of SR in threshold based systems has received considerable attention in recent years [1–11]. In such systems it is well known that,

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via the SR effect, the addition of noise can lead to an enhancement of the system's response to subthreshold signals. Initial studies used sinusoidal input signals and the output signal-to-noise ratio (SNR) to characterize the SR effect – the effect manifests itself as a noise induced maximum in the SNR [6]. Many of these studies were restricted to cases with periodic input signals, which is somewhat limiting from a practical standpoint as many systems of interest are driven by non-periodic inputs. More recently, SR has been extended to include aperiodic broadband signals [7]. SR with aperiodic signals has also been characterized by the traditional measures of cross-correlation coefficient [7–9] and mutual information [4,10].

A new form of SR has recently been introduced under the name of suprathreshold stochastic resonance (SSR), since it is not restricted to a small, subthreshold signal [12–14]. It operates with signals of any amplitude. SSR occurs in an array of threshold devices subject to the same input signal, but independent noise, where the output from each device is summed to give an overall output. The distinguishing feature of SSR is that the effect occurs for signals of arbitrary magnitude and not just subthreshold signals.

SSR is important since it significantly extends the mechanisms under which SR, as an improvement by noise, can occur. SSR represents a specifically distinct mechanism under which an improvement by noise can take place in signal processing. Since its introduction [12], research on SSR has been carried out in diverse areas of signal transmission. The performance measures used to quantify SSR were mutual information [12,13,15], signal-to-noise ratio [16], input–output cross-correlation [17] and Fisher information [18]. SSR has been applied to parametric signal estimation tasks [18], for performance enhancement of an insect vision motion detector model [19], to neural coding schemes in cochlear implant devices [20], as a signal quantizer in the presence of additive threshold noise [21], for signal reconstruction [22] or to enhance signal transduction through arrays of sensory neurons [23]. Studies on SSR also include behaviour of SSR arrays with a very large number of devices [24] and on the optimality of SSR [25]. A very recent and interesting work on the use of SSR is demonstrated in SNR amplification in arrays of sensors which are considered as threshold free nonlinear saturating devices [26].

In earlier work [1] we demonstrated that conventional SR in a single threshold device does not occur with all signals. Whether SR occurs or not depends crucially on the probability density of the signal. For signals with long tails in their distribution – such as exponentially distributed signals – SR is not observed. This observation potentially impacts on other areas of SR research. For example, it has been proposed that inherent noise sources enhance signal transduction in the human ear by the mechanism of SR [27–30]. It is proposed that the Brownian motion of the stereocilia of inner hair cells (IHCs) in the cochlear fluid does not reduce the sensitivity of the transmitted signal but enhances it by the mechanism of SR [28,29]. The maximum sensitivity of the hair cells is achieved with a critical value of noise which is approximately the amount provided by the Brownian motion of the surrounding fluid [28]. Recent research has also shown that the threshold for pure tone detection by the human ear is decreased in the presence of added noise for cochlear implant and normal listeners [31]. More recently, the positive effects of noise on cochlear implant listeners' ability to detect suprathreshold signal modulation were confirmed [32].

However, all this research is based on the use of sinusoidal signals or pure tones. Generally the signals received by the human ear are more complex in nature, like speech or music, which are often modelled as double exponentially distributed [33] or have distributions that slowly decay. From the previous work [1], it has already been proved that SR effect does not occur for signals with double exponential distributions. It has also been seen that the SR effect is dependent on the nature of the input signal distribution, nature of noise and also the threshold of the system [1,11]. This is a constraint in SR based performance enhancement of real time systems as the nature of the input signal distribution cannot be predetermined. This work aims to overcome this limitation by using suprathreshold stochastic resonance (SSR) instead of SR to enhance signal transmission.

2. System description and implementation

SSR is observed in the response of a parallel array of identical nonlinear threshold based devices. Each device is subjected to the same input signal but independent noise as shown in Fig. 1. In principle, the threshold level of each device is also independently adjustable but here all thresholds are equal. The result is to make each of the identical devices generate a distinct output in response to the same common input signal. The indi-