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Experimental investigation of noise-assisted information transmission and storage via stochastic resonance

G.A. Patterson [a], A.F. Goya [a], P.I. Fierens [b,*], S.A. Ibáñez [b], D.F. Grosz [b,c]

[a] Departamento de Física, FCEN, Universidad de Buenos Aires, Intendente Güiraldes 2160, C1428EGA, Buenos Aires, Argentina
[b] Instituto Tecnológico de Buenos Aires, Av. Eduardo Madero 399, C1106ACD, Buenos Aires, Argentina
[c] Consejo Nacional de Investigaciones Científicas y Técnicas, Av. Rivadavia 1917, C1033AAJ, Buenos Aires, Argentina

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ABSTRACT

We present experimental results on the information transmission and storage via stochastic resonance in circuits designed and built around Schmitt triggers (STs). First, we investigate the performance of a transmission line comprised of five STs and show it to exhibit stochastic resonance. Each ST in the line is fed with white Gaussian noise, and the first ST is driven by a non-return-to-zero pseudo-random bit sequence with sub-threshold amplitude. Parameters such as bit error rate (Q-factor) are measured (calculated) and shown to exhibit a minimum (maximum) for an optimum amount of noise. Interestingly, we find that system performance degrades with the number of STs as if the system were linear and impaired only by additive Gaussian noise. We then propose and build a 1-bit storage device based on two STs in a loop configuration. We demonstrate that such a system is capable of storing one bit of information only in the presence of noise, and that there is a regime where the efficiency of such a device increases with increasing noise.

Our results point to the feasibility of building 'blocks' that can transmit, store and eventually process information, whose performance is not only robust against noise, but can actually benefit from it.

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1. Introduction

Consider a particle in a symmetric bistable potential driven by a harmonic force which is too weak to move the particle from one equilibrium state to the other. The addition of noise may help the driving force to 'push' the particle across the potential barrier. If noise power is low, particle jumps are more likely in the direction of the driving force, i.e., the harmonic drive acts by tilting the potential in one direction and particle jumps are governed by Kramer's escape rates [1]. If noise power is increased, mean escape times become small with respect to the drive period and particle jumps become essentially synchronized with the harmonic force. If noise power is increased even further, the behavior of the particle is dominated by the noise and switches erratically between stable equilibria. The observation of this phenomenon in a nonlinear system where the noise helps, an otherwise weak signal, to induce transitions between stable equilibrium states is known as *stochastic resonance* (SR). It was first introduced in the context of climate dynamics [2] to explain the almost periodic occurrence of ice ages, and has since been reported in a large number of areas, ranging from biological and neurological systems [3–5], information transmission sustained by noise [6–10], to information storage [11,12] and information processing [13–15]. For a general review of the area of stochastic resonance we refer the reader to Refs. [16,17].

* Corresponding author. Tel.: +54 11 6393 4800x5873; fax: +54 11 6393 4811.
E-mail address: pfierens@itba.edu.ar (P.I. Fierens).

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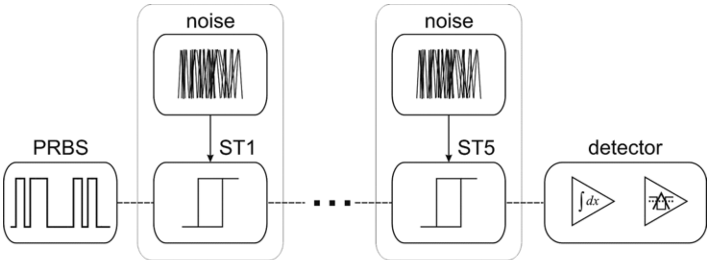

Fig. 1. Schematic setup of the stochastic-resonant transmission line. PRBS: pseudo-random bit sequence. ST: Schmitt trigger. Detector: takes an average of the signal level and compares it to a fixed threshold.

Stochastic resonance has been observed not only in isolated bistable potentials, but also in systems of coupled potentials. In particular, dynamic systems comprised of a chain of forward-coupled double-well potentials driven by a harmonic signal were shown to sustain noise-assisted fault-tolerant propagation [18,19]. It is then only natural to investigate the possible application of the SR phenomenon to digital transmission lines; systems operating in such regime not only would be more resilient to noise degradation, but information transmission itself would be sustained by noise. Investigations in this direction have been carried out [9,20–25], for instance, in the context of a diode nonlinearity [20] and Vertical Cavity Surface Emitting Lasers (VCSELs) [21], in both cases for a single element, and in tunable delay lines [22].

A simple way to implement a 'discrete' model of a double-well potential is provided by Schmitt triggers [26]; a Schmitt trigger (ST) is a bistable electronic device with a hysteretic input–output relation. In Ref. [27] a system consisting of four in-series Schmitt triggers was built and shown to exhibit SR, and to sustain propagation of a harmonic signal with no encoded information. In this paper we perform an experimental investigation of the transmission properties of a line comprised of five in-series Schmitt triggers from the point of view of a communication system. In this sense, our ST line can be regarded as a simple model for a information transmission system with in-line signal regenerators (a similar view was adopted in Ref. [28]).

We then propose and build a 1-bit storage device based on two STs in a loop configuration. We demonstrate that such a system is capable of storing one bit of information only in the presence of noise, and that there is a regime where the efficiency of such a device increases with increasing noise.

The remaining of the paper is organized as follows. In Section 2 we present results on the ST transmission line and, in Section 3, we show results on the 1-bit stochastic-resonance memory device. Finally, in Section 4 we draw our conclusions.

2. Transmission line

The schematic setup of the ST transmission line is shown in Fig. 1. The first ST in the chain is driven with a pseudo-random bit sequence (PRBS) at a rate of 1 KHz, mixed with noise with an adjustable signal-to-noise ratio. The noise is generated by low-pass filtering of a second PRBS generator working at a rate of 250 kHz [29]. Since the filter cutoff 3-dB bandwidth is chosen greater than 10 KHz, the noise spectral density is flat in the studied range and noise can be regarded as White Gaussian Noise (WGN). The data modulation format is Non-Return to Zero (NRZ), a modulation format commonly encountered in high-speed transmission systems [30], with 'low' and 'high' amplitudes of 0 V and 2.8 V, respectively. Since the thresholds of the STs are set to −0.6 V and 3.4 V, STs can only switch between states, and hence the transmission line only works, in the presence of added noise. Finally, the driving signal of every other ST consists of the output of the preceding ST plus WGN from an independent generator.

In Fig. 2 we show the measured BER as a function of the (same) noise intensity fed into each ST. The transmitted sequence consists of a 1000-bit NRZ stream. We implemented a simple receiver that samples every received bit around its midpoint and takes an average over one half of the bit slot; this way, we minimize errors originating from either timing jitter or delayed system response. The receiver threshold was chosen to minimize the BER.

A minimum BER is observed for an optimum noise intensity, the signature of stochastic resonance. At the output of the first ST no errors were recorded around the optimum noise point, so we set the BER $= 10^{-3}$. At the third ST we can still observe a point of optimum noise although, as expected, performance is degraded since BER $\approx 2 \times 10^{-2}$. At the line output, performance is flat and almost constant for a broad range of added noise. This way, the ST line behaves as a robust transmission system, delivering constant BER almost independently of noise in the studied range.

A convenient measure of signal quality, commonly encountered in the literature of communication systems, is provided by the so-called 'Q-factor'. It is computed as

$$Q = \frac{V_1 - V_0}{\sigma_1 + \sigma_0}, \tag{1}$$

where $V_{1,0}$ is the average of the sampled value of the decoded 1,0 bits, and $\sigma_{1,0}$ is the corresponding standard deviation [30,31]. As such, a large Q-factor indicates good contrast between received 0 and 1 states and, therefore, it is easier for the receiver to distinguish between the two.

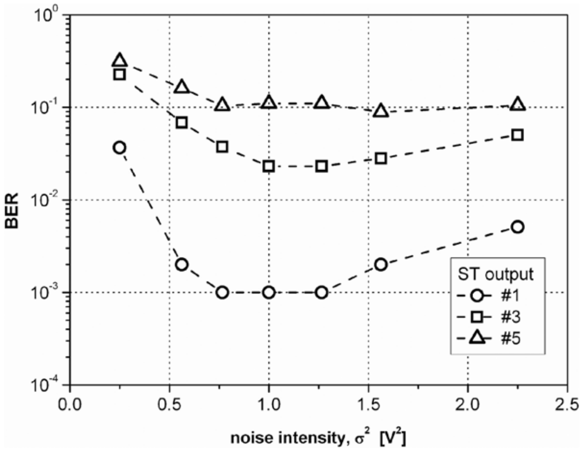

Fig. 2. Measured Bit Error Rate (BER), at the output of the 1st, 3rd and 5th ST. There is an optimum noise range that minimizes the BER.

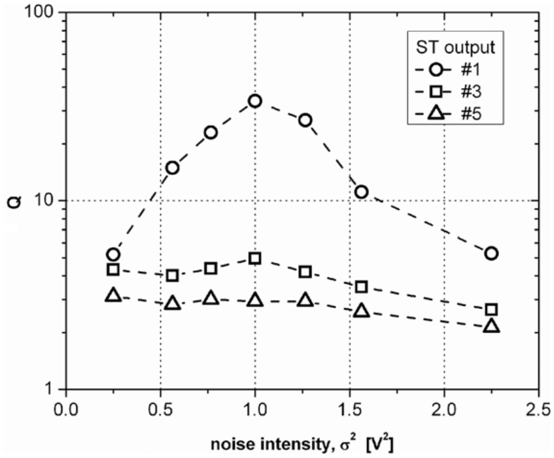

Fig. 3. A measure of signal quality: Q-factor calculated from the output bit stream at the 1st, 3rd, and 5th ST. The transmission line shows resilience to added noise.

Results of Q-factor vs. noise intensity are shown in Fig. 3 at the output of the first, third, and fifth STs, respectively. At the first ST we observe another signature of stochastic resonance namely, a maximum Q for an optimum noise input. At the line output we also observe a flat response, as in the case of the measured BER.

It should be noted that, in the context of communication systems, it is customary to associate a Q-factor with a BER. This usually works well in the regime of linear transmission. However, the system considered in this paper is not linear and, therefore, Q has no a priori relation to the BER [31], although it still provides a quantitative measure of signal quality.

In order to further investigate transmission performance, we looked at the minimum BER (optimum noise) at the output of each ST, i.e., performance vs. ST number. Results are shown in Fig. 4. It is interesting to compare these results with the degradation expected in a system periodically impaired by Additive White Gaussian Noise (AWGN) every n-th node, as it would be the case of a system with in-line amplification [31]. For such a system, it is easy to show that the BER scales with distance as

$$\mathrm{BER}(n) = \frac{1}{2}\mathrm{erfc}\left(\frac{C}{\sqrt{n}}\right), \tag{2}$$

where erfc is the complementary error function, n is the node number, and the constant C is chosen to fit the BER of the second Schmitt trigger. We chose the second ST, and not the first, since we measured BER for the former and only have an upper limit for the latter. Remarkably, even though the ST stochastic line is a nonlinear system, performance degradation follows that of a transmission system impaired only by additive Gaussian noise. In Ref. [25] numerical results on a line of bistable double-well potentials showed performance degradation with the number of bistable elements that exceeded that of a linear system. This observation occurred for certain coupling regimes. It remains to be studied whether such a behavior can be replicated with a system of discrete STs.

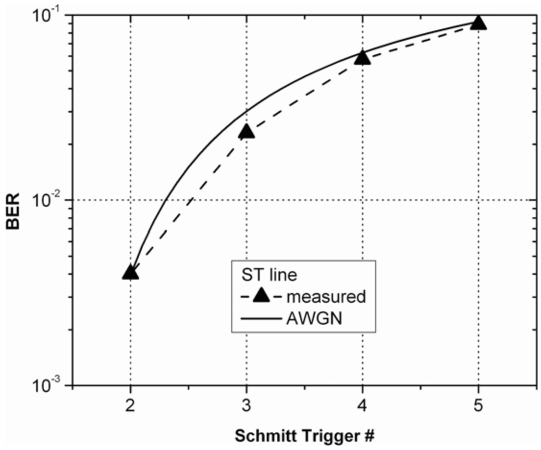

Fig. 4. Minimum BER compared to that of a system impaired only by additive white Gaussian noise. Interestingly, although the system is nonlinear, performance degradation with distance follows that of a linear system.

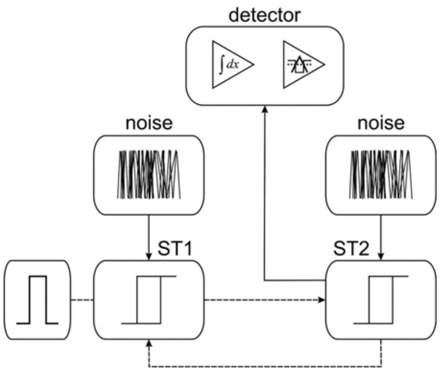

Fig. 5. A schematic view of a 1-bit memory device comprising two STs in a loop configuration.

3. Stochastic-resonance memory device

In this section we show how the ST transmission line can be modified to produce a 1-bit memory device. In Ref. [11,12] it was shown that a transmission line, comprising forward-coupled bistable oscillators fed with noise and closed in loop fashion, could sustain an stationary wave long after the driving harmonic wave was switched off. Based on this scheme, we look at the simplest system one can build with the discrete version of the bistable oscillators, i.e., the ST circuits. The schematics of the proposed device are shown in Fig. 5. A single bit, representing the '1' state that we want to store in memory, is fed into the first ST with a supra-threshold amplitude of +5 V and duration $T_B = 1$ ms. The ST thresholds are set to +3 V and −1 V, respectively. The high and low output levels of both STs are set to sub-threshold values of +2 V and 0 V, respectively. The output of the first ST is used to drive the second ST. Then, the output of the second ST is fed back into the first ST.

During the time when the system is not driven, we interrogate the second ST at intervals of T_B. The detector averages the received amplitude over a fraction of a bit slot and compares it to a fixed threshold, in order to make a decision between a '1' and a '0' [30]. Averaging helps reduce the influence of timing jitter and limited bandwidth of the circuits. Finally, we repeat this procedure 1000 times, alternating the initial state of the second ST, and compute the bit error rate by counting the number of times a '0' state was detected.

In Fig. 6 we show the measured BER as a function of noise intensity and elapsed time, in units of T_B. For low noise intensities, the BER is 1/2 because the sub-threshold output of the first ST is not strong enough to change the second ST state by itself. It can also be observed that there is a range of noise that minimizes the BER, the signature of stochastic resonance. In this range we computed no errors, i.e., the BER is better than 10^{-3}. Since the input signal lasts only one T_B and noise is continuously fed at the input of both STs, we expect the BER to increase with time. However, around the optimum noise intensity, device performance does not show degradation with time. This is an interesting result as it points to a device whose performance, not only can benefit from added noise, but it is also robust in a noisy environment.

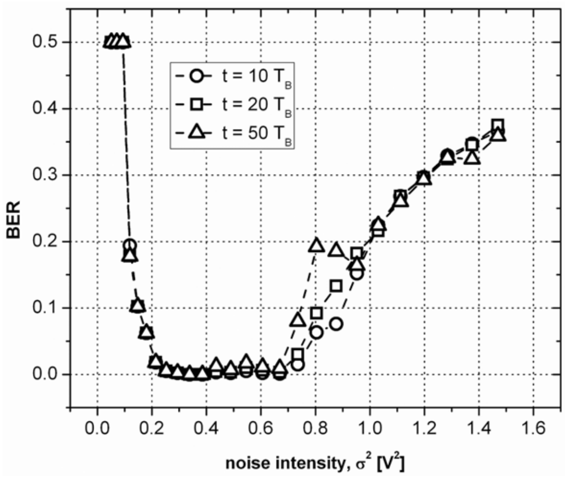

Fig. 6. Memory performance as a function of the noise intensity and time.

4. Conclusions

In summary, we experimentally investigated the performance of a transmission line comprised of five Schmitt triggers, where each ST was fed with white Gaussian noise and the first ST was driven by a pseudo-random sequence of non-return-to-zero bits. This line can only transmit information in the presence of noise as each ST is driven by a sub-threshold signal. Signal-quality parameters such as bit error rate (Q-factor) were measured (calculated) and shown to display a minimum (maximum) for an optimum noise level, a signature of stochastic resonance. Although the system is nonlinear, performance degradation vs. distance was shown to follow that expected from a linear system impaired only by additive Gaussian noise.

Finally, we showed how two STs can be connected in a loop configuration to produce a 1-bit stochastic-resonance memory device. Information storage only occurs in the presence of noise and device performance is robust with time in a wide range of noise around the optimum.

We believe that the results presented in this paper open up the possibility of designing and building devices than can transmit, store, and eventually process information, that are not only resistant to environmental noise, but their performance can actually benefit from it.

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