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Filtering as a Way of Varying the Characteristics of Intermittent Behavior in Two Unidirectionally Coupled Tunnel Diode Generators

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Abstract—The intermittent behavior that can occur in chaotic systems upon signal filtering near the boundary of the chaotic phase synchronization regime is studied. It is found that in a system of unidirectionally coupled tunnel diode generators, it is possible for the eyelet and the ring intermittencies to exist simultaneously near the boundary of phase chaotic synchronization when a filter with certain parameters used.

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INTRODUCTION

Numerous studies have established that intermittent behavior is characteristic of nonlinear dynamic systems. Intermittency is often observed upon transitioning from periodic to chaotic oscillations, and at the boundary of the onset of various chaotic synchronization regimes of coupled oscillators [1, 2].

There is now a system for classifying intermittency; it includes type I–III intermittencies [3], on-off intermittency [4], eyelet intermittency [5], and ring intermittency [6]. Despite the similarity between intermittencies of different types (i.e., the existence of two different time-intermittent regimes in a time series), each one has its own specific features and characteristics (e.g., the dependence of the average time of laminar phases on the governing parameter, and the distribution of the laminar phase times at fixed values of the governing parameters). In addition, it should be noted that the mechanisms responsible for intermittent behavior are different for each type.

Recent research has shown that a more complicated type of behavior is possible in nonlinear dynamic systems when intermittencies of two different types exist simultaneously. Such behavior is referred to as the intermittency of intermittencies [7, 8]. In nonlinear dynamic systems, such behavior is apparent in the simultaneous existence of two different mechanisms that initiate turbulent periods of behavior, and therefore in the simultaneous existence of intermittencies of two different types.

A great deal of attention is now being given to studying the intermittency of intermittencies. In [7], the possibility of ring and eyelet intermittencies existing simultaneously was demonstrated via the example of unilaterally coupled Roessler systems, and the possibility of ring and type I intermittencies coexisting was established for a Van der Pol oscillator with noise [8]. It is worth mentioning that the coexistence of two different types of intermittent behavior can be observed when the behavior of a system is studied on definite time scales introduced through continuous wavelet transformation. In other words, a definite scale of observation should always be chosen when studying the behavior of model systems, in order to detect the intermittency of intermittencies [9]. In real systems, however, it is possible that the intermittency of intermittencies will arise automatically without the researcher choosing any scale of observation. It is well known that the continuous wavelet transformation with a Morlet mother wavelet used to study the behavior of systems on different time scales, and to detect time scale synchronization [10], can be considered a filter that affects the analyzed signal [11]. It is therefore quite possible that when studying real systems in which a signal that displays a certain type of intermittent behavior is subjected to prefiltering, either by a filter that is part of the system under study or a filter in the coupling channel that ensures the transmission of the signal, we might observe intermittency of intermittencies even without investigating the system's dynamics on different time scales.

In this work, we study the intermittent behavior that can occur in chaotic systems upon filtering signals near the boundary of the phase chaotic synchronization regime. It was found that in a system of unidirectionally coupled tunnel diode generators [12], two dif-

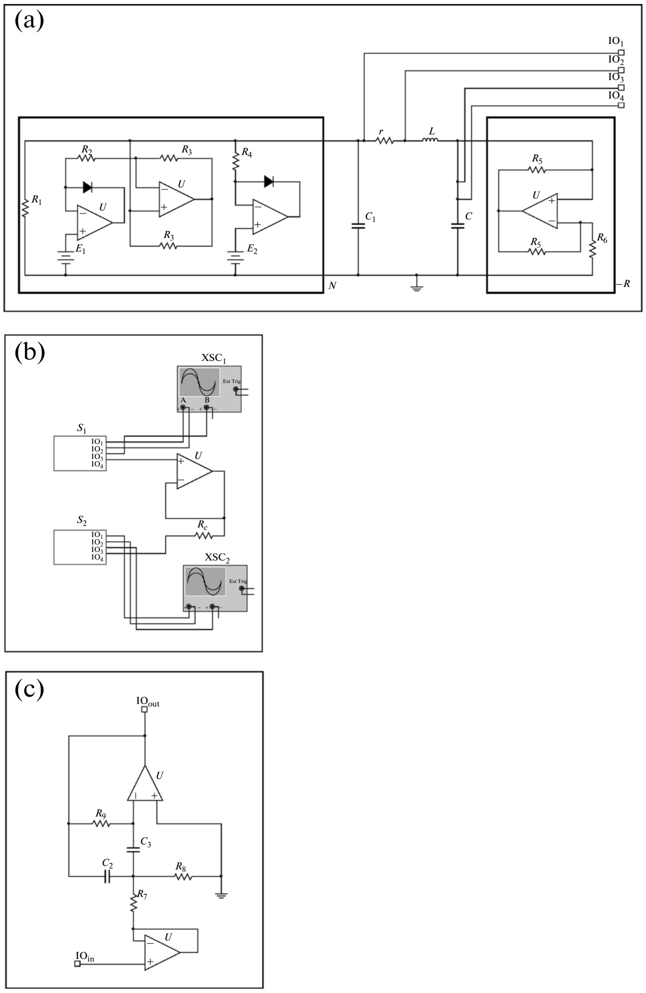


Fig. 1. (a) Scheme of our piecewise-linear model of a Kiyashko–Pikovskii–Rabinovich generator, (b) coupling circuit of two piecewise-linear models of a Kiyashko–Pikovskii–Rabinovich generator, and (c) circuit of the band-pass filter used in this work.

ferent types of intermittent behavior can exist simultaneously near the boundary of chaotic phase synchronization when a filter with certain parameters is used.

A SYSTEM OF UNIDIRECTIONALLY COUPLED TUNNEL DIODE GENERATORS

We used a unidirectionally coupled tunnel diode generator system [12] to study the intermittent behavior that occurs near the boundary of chaotic phase synchronization upon filtering signals with different parameters. Our simulation in the unidirectionally coupled tunnel diode generator system was performed using the NIMultisim 9.0 professional and educational circuit layout environment. The schematic diagram of a piecewise-linear model of a Kiyashko–Pikovskii–Rabinovich generator is shown in Fig. 1a, where unit (*N*) is a nonlinear element that is a piecewise-linear approximation of a tunnel diode with an *N*-shaped volt-ampere characteristic. Unit (-*R*) in Fig. 1a is a gyrator that provides negative resistance. *D* denotes ideal diodes and *U* indicates ideal operational amplifiers. The parameter values are $C_1 = 2$ nF, $C = 6.8$ nF, $r = 200\ \Omega$, $E_1 = 0.085$ V, $E_2 = 0.5$ V, $R_1 = 51.5\ \Omega$, $R_2 = 45\ \Omega$, $R_3 = 120\ \Omega$, $R_4 = 154.155\ \Omega$, $R_5 = 3.6$ kΩ, and $R_6 = 1.5$ kΩ. Parameter L was determined separately for each system. The circuit has four outputs, three for recording the voltages that are dynamic variables and one to couple the systems.

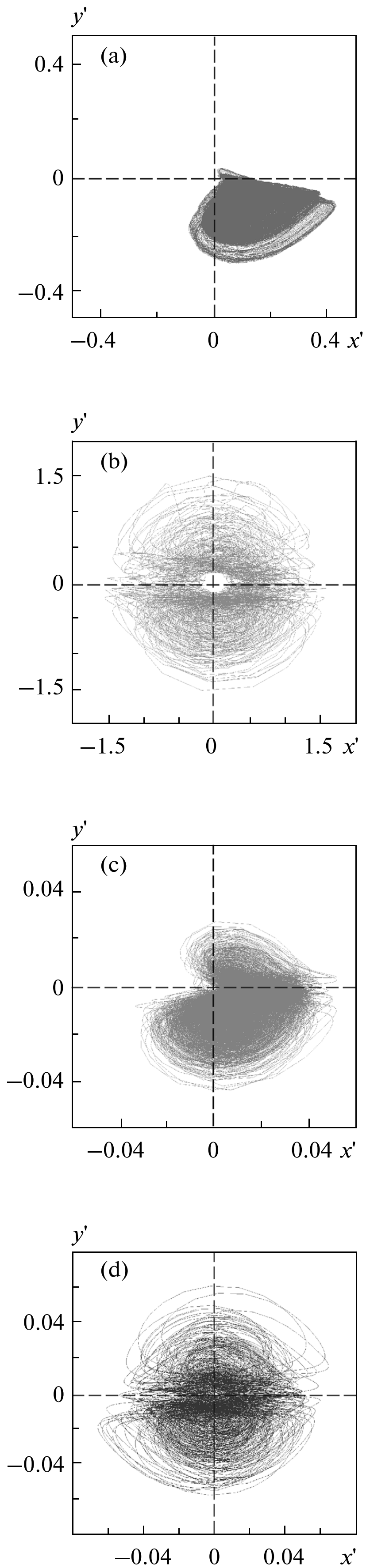
The coupling circuit of our two piecewise-linear models of the Kiyashko–Pikovskii–Rabinovich generator is shown in Fig. 1b. System S_1 is unidirectionally coupled with system S_2 through an operational-amplifier-based repeater. Resistance R_c controls the coupling; the greater the parameter, the weaker the coupling between the systems and vice versa. The systems are identical except for parameter L: $L = 3.2$ mH for system S_1 and $L = 3.1$ mH for system S_2. The voltages are recorded by two double-channel oscilloscopes.

The circuit of the band-pass filter used in our study is shown in Fig. 1c. The parameter values are $C_2 = 0.4$ nF, $R_7 = 1.591549$ MΩ, $R_8 = 10.61$ MΩ, and $R_9 = 11.93662$ MΩ. Parameter C_3 is used to adjust the filter's frequency band center.

EFFECT OF SIGNAL FILTERING ON INTERMITTENT BEHAVIOR NEAR THE BOUNDARY OF THE CHAOTIC PHASE SYNCHRONIZATION REGIME

It should be noted that the effect signal filtering has on the behavior of the unidirectionally coupled tunnel diode generators described above was studied near the boundary of the chaotic phase synchronization regime. We found that in a system of two unidirectionally coupled piecewise-linear models of Kiyashko–Pikovskii–Rabinovich generators, the chaotic phase synchronization regime is triggered with coupling parameter $R_c = 12.5$ kΩ when there is a low-frequency mismatch between the generators.

In addition, it was shown that intermittent behavior occurs when there is considerable detuning of the frequency blocked by the filter relative to the system's natural frequency. According to [9], ring intermittency then arises in the system. The situation is somewhat different when a system of two unidirectionally coupled piecewise-linear models of a Kiyashko–Pikovskii–Rabinovich generator is close to the region ahead of chaotic phase synchronization and the signal is filtered with considerable detuning of the frequency blocked by the filter relative to the system's natural frequency. Two different types of intermittent behavior can be observed simultaneously: ring and eyelet. We based our conclusions on investigations of the behavior of systems on a rotating plane, as was done in [9]. This approach requires that we consider vari-



ables (the voltages on capacitance C and resistances r, $x^{1.2} = U_r^{1.2} = I0_1^{1.2} - I0_2^{1.2}$ and $y^{1.2} = U_C^{1.2} = I0_3^{1.2}$) on a plane that revolves around the coordinate origin [6]:

$$
\begin{aligned}
x' &= x^2 \cos \varphi_1(t) + y^2 \sin \varphi_1(t), \\
y' &= -x^2 \sin gj_1(t) + y^2 \cos \varphi_1(t),
\end{aligned}
\tag{1}
$$

where $\varphi_1(t)$ and $\varphi_2(t)$ are the instantaneous phases of the investigated chaotic systems, respectively. Phases $\varphi_1(t)$ and $\varphi_2(t)$ can be considered in different ways, e.g., as the angle of rotation on the plane of the chaotic attractor's projection, or using the Poincare section or the Hilbert transform [13].

Figure 2 shows the behavior of the phase path on a rotating plane. We can see that if the signal is not filtered, eyelet intermittency is observed in the system (Fig. 2b) with coupling parameters below R_c. When the coupling parameter is higher than R_c, synchronous behavior is observed in the system (Fig. 2a). Upon filtering of the original signal with considerable detuning relative to the system's natural frequency but with the coupling parameter above R_c, ring intermittency is observed in the system (Fig. 2c). If the coupling parameter is below R_c, ring and eyelet intermittencies can be observed in the system simultaneously, as was the case in [7, 8].

CONCLUSIONS

We studied the intermittent behavior that can occur in chaotic systems upon filtering the original signal near the boundary of the chaotic phase synchronization regime. Using the example of unidirectionally coupled piecewise-linear models of a Kiyashko–Pikovskii–Rabinovich generator, it was shown that eyelet and the ring intermittencies can exist simultaneously near the boundary of the chaotic phase synchronization when a filter is used with considerable detuning relative to the system's natural frequency. Our findings show that the simultaneous existence of two different types of intermittent behavior in real radiophysical systems is a fairly typical phenomenon.

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Fig. 2. Motion of the phase path on a rotating plane with (a) synchronous behavior, (b) with eyelet intermittency, (c) with ring intermittency, and (d) with the simultaneous existence of eyelet and ring intermittencies.

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