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Do chaos-based communication systems really transmit chaotic signals?

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ABSTRACT

Many communication systems based on the synchronism of chaotic systems have been proposed as an alternative spread spectrum modulation that improves the level of privacy in data transmission. However, depending on the map and on the encoding function, the transmitted signal may cease to be chaotic. Therefore, the sensitive dependence on initial conditions, which is one of the most interesting properties for employing chaos in telecommunications, may disappear. In this paper, we numerically analyze the chaotic nature of signals modulated using a system that employs the Ikeda map. Additionally, we propose changes in the communication system in order to guarantee that the modulated signals are in fact chaotic.

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1. Introduction

Non-linear systems and chaos have been applied in all areas of engineering [1]. This fact is particularly true when it comes to Signal Processing and Telecommunications, especially after the works by Pecora and Carroll [2] and Ott et al. [3]. Chaos has appeared in different areas as digital and analog modulation, cryptography, pseudorandom sequences generation, watermarking, nonlinear adaptive filters, phase-locked loop networks, among others (see e.g., [4–13]).

Three defining properties of chaotic signals are their boundedness, aperiodicity and sensitive dependence on initial conditions (SDIC) [14]. This last property means that, if the generator system is initialized with a slightly different initial condition, the obtained signal quickly diverges from the original one. These three properties all together are necessary for a signal to be called *chaotic* and are the basis for the alleged advantages of using chaos in communications, as an improvement in security [15]. However, in almost all chaos-based communication schemes proposed in the literature, the facts that there is a nonlinear system that, when isolated, generates chaotic signals and that the transmitted signals are apparently aperiodic are taken as sufficient evidence of chaos, without further investigation. The SDIC is taken for granted. This is partly due to the fact that when it comes to practical applications, to verify the SDIC is not immediate.

As communication systems are always related to the transmission of probabilistic aperiodic messages, it becomes non-trivial and of paramount importance to detect if the aperiodicity in the transmitted signals comes from the nonlinearity of the transmitter or from the message itself, in which case the chaos advantages are not really present. This issue is particularly relevant when the non-linear system employed presents a stable fixed point besides the chaotic attractor. From one temporal

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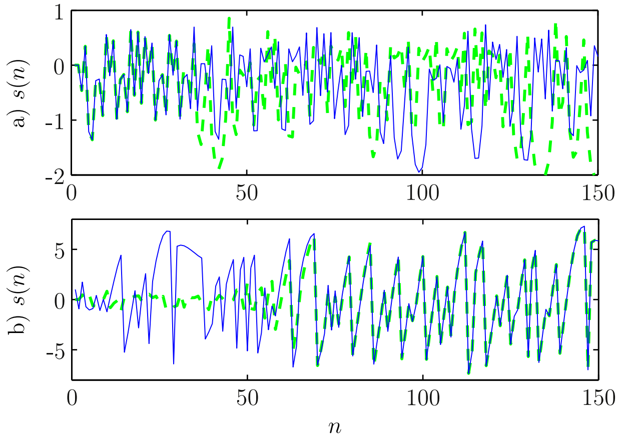

Fig. 1. Examples of (a) chaotic and (b) non-chaotic signals concerning sensitive dependence on initial conditions. (a) Two aperiodic orbits with very close initial conditions turning into different signals after some iterations. (b) Two signals starting with different initial conditions leading to the same orbit after some iterations.

series it is hard to visually distinguish a chaotic signal stepping through the chaotic attractor and an orbit converging to the fixed point but continuously perturbed. The difference is only in terms of SDIC.

As an example, Fig. 1(a) shows the expected behavior of chaotic signals. Two aperiodic orbits with very close initial conditions are shown. After approximately 40 samples they become apart in the state space, clearly presenting SDIC. In contrast, the signals in Fig. 1(b) does not present SDIC. Starting from different initial conditions, they start to follow almost the same path after approximately 70 samples. Although bounded and aperiodic, the signals in Fig. 1(b) are not chaotic.

The usual technique to evaluate the SDIC is via Lyapunov Exponents (LE) [14]. The Lyapunov numbers are the average per-step exponential divergence rate of nearby points along an orbit, one for each direction, and the LE are the natural logarithm of the Lyapunov numbers [14]. Given a deterministic map, it is relatively straightforward to numerically evaluate the LE of its orbits [14]. However, when it comes to chaos-based communication systems proposals where the message to be transmitted is fed back in the chaotic signal generator (CSG) [16–19], complications may appear.

Bearing all these in mind, in this paper we analyze the chaos-based communication system proposed in [19] in order to verify if the transmitted signals are in fact chaotic. Ref. [19] employed a particular codification scheme in order to implement an efficient communication system based on Ikeda map [14,20]. This map was considered in [19] since it can be envisioned as arising from a string of light pulses impinging on a partially transmitting mirror of a ring cavity with a nonlinear dispersive medium, and therefore, can be used to model a discrete-time low-pass version of the optical communication scheme of [15]. However, caution must be taken, once that the Ikeda map presents co-existing attractors with close basin of attractions: a stable fixed point and a chaotic attractor [14]. This particular structure can possibly generate some drawbacks for the conception of efficient chaos-based communication systems, presenting apparently aperiodicity with lack of SDIC. Therefore, in this work, a more detailed analysis concerning the presence and the consequences of dealing with co-existing attractors is performed and illustrated by a representative set of simulations. Furthermore, a strategy guided by the LE associated with such attractors is adopted for suitably defining the amplitude of the message in order to guarantee a truly chaos-based system.

The paper is organized as follows. In Section 2, we review the system used in [17–19] and Section 3 describes the main properties of the Ikeda map. In Section 4, we numerically analyze the transmitted signals of [19] and propose changes in the system in order to guarantee that the transmitted signals are truly chaotic. Finally, in Section 5, we draft some conclusions.

2. Problem formulation

Wu and Chua's synchronization scheme proposed in [16] is a simple way to use chaos for communication. They addressed chaotic system synchronization differently from Pecora and Carroll's seminal paper [2]. Instead of using conditional LE to check the asymptotic stability of the slave system and hence the possibility of synchronism, Wu and Chua restated the master and slave equations in such a way that it is easy to verify the convergence of the synchronization error to zero. Based on this synchronization scheme, a communication system was proposed in [16] and a discrete-time version appeared later in [21]. In this section, we succinctly revise these ideas.

Consider two discrete-time systems defined by

$$\mathbf{x}(n+1) = \mathbf{A}\mathbf{x}(n) + \mathbf{b} + \mathbf{f}(x_i(n)) \tag{1}$$

$$\hat{\mathbf{x}}(n+1) = \mathbf{A}\hat{\mathbf{x}}(n) + \mathbf{b} + \mathbf{f}(x_i(n)) \tag{2}$$

where $n \in \mathbb{N}$ represents time instants, $\mathbf{x}(n)$ and $\hat{\mathbf{x}}(n)$ are real-valued column vectors of length K, i.e, $\mathbf{x}(n) = [x_1(n)\ x_2(n)\ \ldots\ x_K(n)]^T$ and $\hat{\mathbf{x}}(n) = [\hat{x}_1(n)\ \hat{x}_2\ (n)\ \ldots\ \hat{x}_K(n)]^T$, x_i and $\hat{x}_i$ represent states of the system with $i = 1,\ldots,K$, and $(\cdot)^T$ stands for transposition. $\mathbf{A}$ is a square matrix and $\mathbf{b}$ a column vector, both constants, real-valued and of

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