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Research Article

Bio-Inspired Nonlinear Oscillator Based on ECG and EEG Bio-Emulator Signals

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Abstract **–**Nonlinear signals have been extensively utilized in encryption and decryption applications, representing a significant area of research within chaos theory. Such signals are highly sensitive to initial conditions and system parameters; consequently, even minor variations in the underlying mathematical formulation can produce substantially different nonlinear waveforms, a phenomenon commonly referred to as the butterfly effect. Electrocardiographic (ECG) signals, which reflect the fundamental physiological activity of the human heart, and electroencephalographic (EEG) signals, which are closely related to cerebral activity and influenced by blood flow dynamics, also exhibit nonlinear characteristics due to their intrinsic nonlinear and complex structures. In this study, a novel bio-inspired nonlinear oscillator with two outputs is proposed, incorporating ECG and EEG signals. Unlike classical nonlinear oscillators reported in the literature, such as the Chua, Sprott, and Lorenz systems, which are primarily based on idealized mathematical models, the proposed oscillator integrates physiological signal dynamics. This integration enables the generation of distinct nonlinear signals corresponding to different heart rhythms for use in encryption and decryption processes, thereby enhancing the robustness and security of data transmission.

Keywords – Chaos, Oscillator, ECG, EEG, Logistic Map and Heart Rhythm

I. Introduction

Cryptography is a fundamental discipline in information security that focuses on the design and analysis of mathematical techniques to ensure confidentiality, integrity, authentication, and non-repudiation of data in digital communication systems. With the rapid growth of networked applications, cloud computing, and Internet of Things (IoT) technologies, cryptographic methods have become essential for protecting sensitive information against unauthorized access and malicious attacks. Modern cryptography integrates concepts from number theory, complexity theory, and computer science to develop robust algorithms that can withstand both classical and emerging computational threats. [1-7]. Cryptography has undergone multiple stages throughout its historical development and has been extensively addressed in the literature as a broad research field [8-9]. The contribution of nonlinear oscillators to cryptography emerged from their ability to ensure the secure transmission of data to the receiver based on the fundamental principles of chaos theory [6]. Chaos theory provides significant advantages for cryptographic applications by enabling the generation of unique electrical signals that do not repeat over time. Another important aspect is the high sensitivity of these signals to initial conditions and system parameters, which further enhances security [4].

To date, in addition to conventional nonlinear oscillators such as those proposed by Sprott and Chua [5, 7], various types of nonlinear systems including memristor-based nonlinear oscillators, hypernonlinear oscillators, and other architectures have been reported in the literature [10-12]. These nonlinear oscillators have been effectively employed for the encryption of different data types, such as audio, image, and video signals.

Similar to nonlinear signals, biosignals generated by the human body namely ECG and EEG signals are produced instantaneously and uniquely for each individual and exhibit nonlinear behavior [1]. Variations in heart rhythm lead to differences in the electrical responses of ECG signals. Consequently, EEG signals may also be indirectly influenced by these variations. Indeed, it has been observed that brain signals vary depending on an individual's health condition [13].

EEG signals represent the combined electrical activity generated by the brain, which is considered the control center of the human body. EEG measurements are widely used for monitoring and evaluating neurological disorders such as epilepsy, Alzheimer's disease, and autism. These signals provide clinicians and researchers with valuable insights into brain processes and offer significant advantages in medical diagnosis based on the extracted information. The electrical signals generated by the brain are transferred to computer environments through EEG sensors.

An EEG signal typically exhibits rhythmic activity within the frequency range of 0–30 Hz. This activity comprises distinct frequency bands, including delta (δ: 1–4 Hz), theta (θ: 4–8 Hz), alpha (α: 8–12 Hz), beta (β: 12–26 Hz), and gamma (γ: >30 Hz). During any brain activity, fluctuations and variations in these frequency bands can be observed [14]. In practical signal acquisition, electrodes for electroencephalogram (EEG) recording are placed on or around the cranial muscles. Depending on different cognitive states such as deep sleep, imagination, creativity, and active thinking EEG components including alpha, beta, theta, and gamma signals are generated in accordance with the corresponding brain activity frequencies [15-16]. Traditional nonlinear oscillators have been widely studied and applied in secure communication, encryption, and signal processing due to their sensitivity to initial conditions and system parameters. However, many existing nonlinear systems exhibit limited dynamic richness and restricted nonlinear behavior, which may reduce their effectiveness in applications requiring high complexity and robustness. Moreover, the integration of biological signals, such as ECG, into nonlinear system design has not been sufficiently explored, although these signals inherently exhibit complex and individual-specific dynamics.

Therefore, this paper proposes a novel nonlinear oscillator with enhanced dynamical richness. The proposed system aims to provide a broader range of nonlinear regimes, increased complexity, and improved robustness against cracking and parameter estimation attacks. The system is validated using ECG-like signals to demonstrate its capability to model complex biological dynamics and to highlight its potential for secure biomedical applications.

II. MATERIALS AND METHOD

This section describes the materials and methods used to develop and evaluate a bio-inspired nonlinear oscillator model based on ECG and EEG bio-emulator signals.

A. *Electrocardiographic signal (ECG)*

The electrocardiographic (ECG) signal plays a crucial role in the detection and diagnosis of cardiac disorders. Accurate analysis of ECG signals provides a significant time advantage in life-saving interventions. Determining whether the heart rhythm is normal or abnormal and subsequently diagnosing the patient's condition to initiate appropriate treatment are of critical importance. ECG signals enable the measurement of cardiac behavior in the form of electrical signals, and the acquired electrical activity is highly effective in assessing the health status of an individual's heart rhythm.

In addition to its clinical significance, ECG signals exhibit nonlinear behavior, which has been demonstrated in several studies under different heart rhythm conditions [1]. This nonlinear nature may vary depending on an individual's heart rhythm, and the influence of coefficients in the underlying mathematical expressions an inherent characteristic of nonlinear systems can also be observed in ECG signal outputs.

The analysis of ECG signals has contributed to saving numerous lives, and contemporary research employs various analytical methods to reduce deaths associated with early-age myocardial infarction. These analyses typically involve the examination of the electrical waveform components of the ECG signal, namely the P, Q, R, S, T, and U waves [2]. The electrical waveform of a typical ECG signal is illustrated in Figure 1.

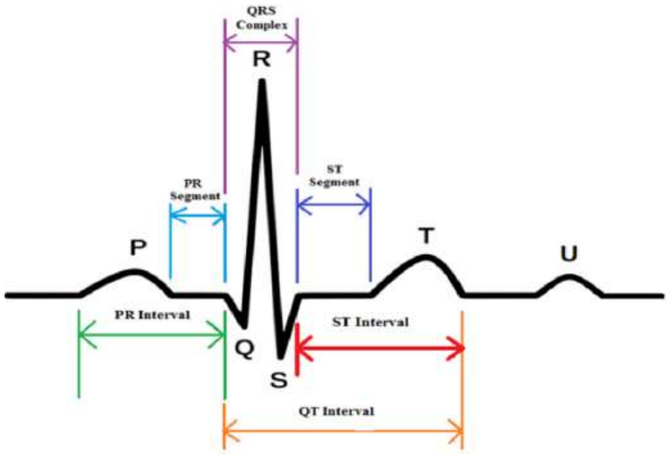

Fig. 1 ECG signal electrical response

The ECG signal of a healthy individual shown in Fig. 1 is represented in a computer environment by a mathematical equation that closely approximates the corresponding physical ECG signal. This mathematical formulation inherently exhibits nonlinear behavior. The governing equations of this model are presented in Eqs. (1) and (2) [3].

$$x_1' = x_1 - x_2 - Cx_1x_2 - x_1x_2^2$$

$$x_2' = Hx_1 - 3x_2 + Cx_1x_2 - x_1x_2^2 + \beta(x_4 - x_2) \tag{1}$$

$$x_3' = x_3 - x_4 - Cx_3x_4 - x_3x_4^2$$

$$x_4' = Hx_3 - 3x_4 + Cx_3x_4 + x_3x_4^2 + 2\beta(x_4 - x_2)$$

$$ECG(t) = \alpha x_1 + \alpha x_2 + \alpha x_3 + \alpha x_4 \tag{2}$$

Based on Eqs. (1) and (2), the ECG signal shown in Figure 2 was obtained using code implemented in a MATLAB *.m* file and a corresponding Simulink model.

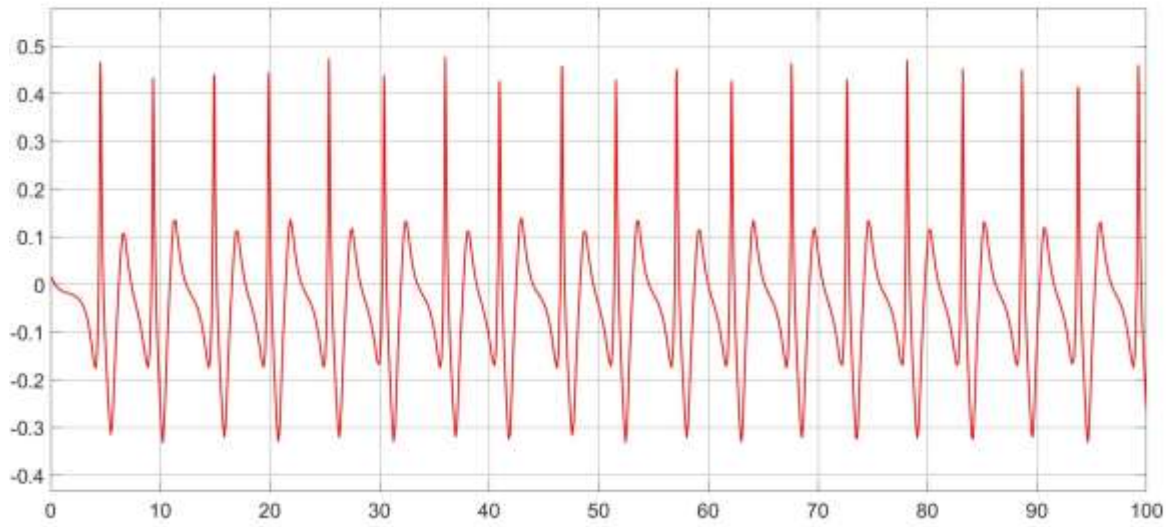

Fig. 2 ECG Matlab Graphic

The obtained ECG signal can be generated not only to resemble that of a healthy individual but also under different heart rhythm conditions. In the subsequent stage, the EEG signal was generated, and by enabling it to produce different responses dependent on the ECG signal, both signals were configured as two distinct outputs of a nonlinear oscillator. Figure 3 illustrates the phase spaces (nonlinear attractors) between the components of the ECG signal.

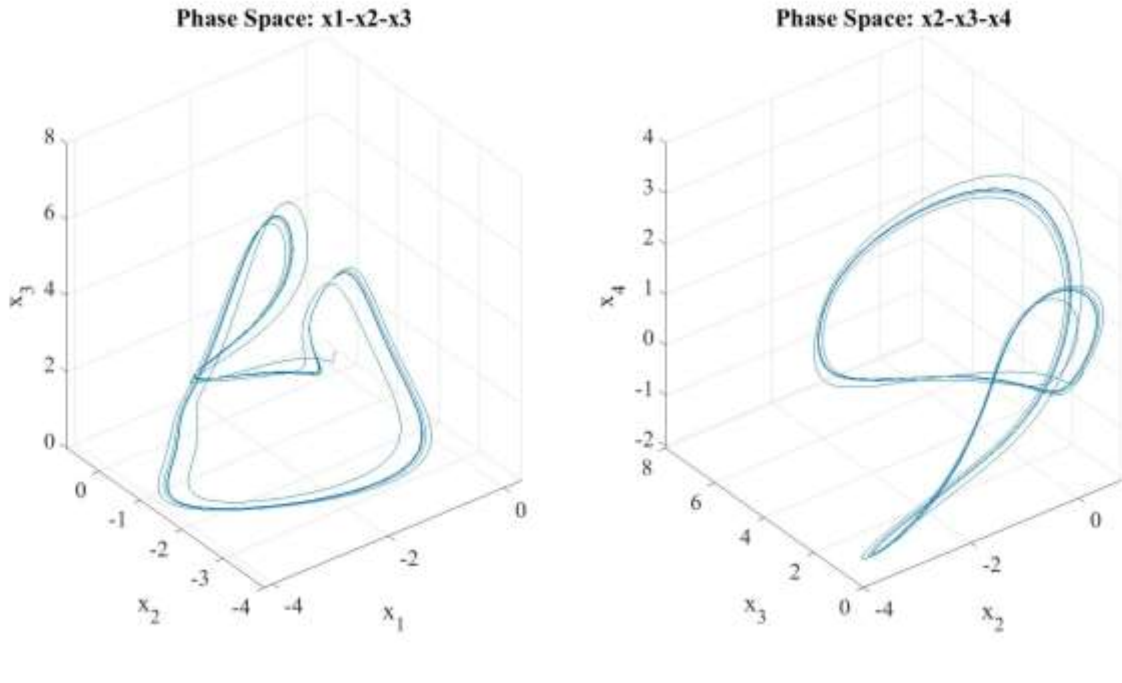

Fig. 3 ECG Phase Space

B. Electroencephalography signal (EEG)

In order to construct a nonlinear oscillator suitable for the proposed next-generation architecture and influenced by the rhythm of the ECG signal, the EEG signal was first generated using the logistic map method. The mathematical equations describing the EEG signal based on the logistic map are presented in Eq. (3) and Eq. (4) [17].

$$\frac{dP(t)}{dt} = k.P(t)$$

$$\frac{dP(t)}{dt} = \alpha P - bP^2 \tag{3}$$

$$\frac{dP(t)}{dt} \approx P(t+\Delta t) - P(t)\Delta t$$

$$P_{n+1} = (1+\alpha\Delta t)P_n - b\Delta t P_n^2$$

$$y_{n+1} = (1+\alpha)y_n(1-y_n)$$

$$v(t) = \begin{cases} 0, & t < 0 \\ \gamma t(2-\gamma t).\exp(-\gamma t), & t \geq 0 \end{cases} \tag{4}$$

$$V(t) = \sum_{k=0}^{N} y_k v(t-k\tau), \quad N\tau < t < (N+1)\tau, \quad N = 0,1,2 \ldots$$

Electrical signals closely resembling real EEG signals were generated using these equations, and modifications were made in the coding to integrate them with the ECG signal. No real human EEG data were used in this study. All EEG signals employed in the proposed nonlinear oscillator were purely synthetic, mathematically generated, and produced via a bio-emulator model. The signals were created to mimic the dynamical characteristics of EEG activity and were used solely for simulation, analysis, and validation purposes. Therefore, this study does not involve any public or private human EEG datasets, and no ethical approval was required.

C. Nonlinear Oscillator based ECG and EEG

By placing the generated ECG signal and the EEG signal, which was produced based on the rhythm of the ECG, within the same framework, the two-output next-generation nonlinear oscillator was prepared for use. The block diagram of this nonlinear oscillator is presented in Figure 4.

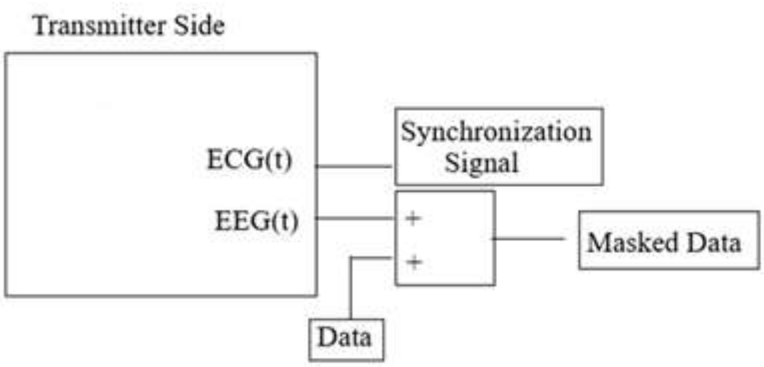

Fig. 4 Nonlinear Oscillator

As shown in Figure 5, the proposed bio-inspired nonlinear oscillator can encrypt data using its two distinct nonlinear outputs. On the receiver side, decryption can be performed by authorized personnel following synchronization with the nonlinear oscillator located at the receiver.

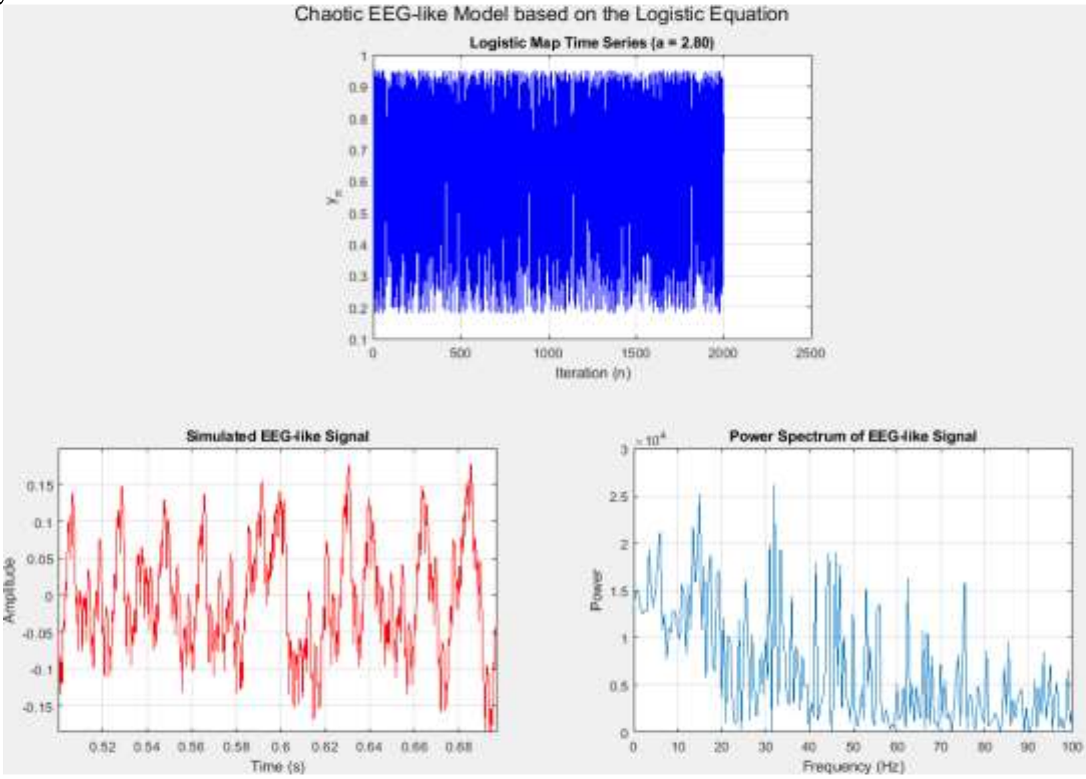

Fig. 5 Simulated EEG-like signal, Power Spectrum and time series

The bifurcation diagram of the EEG signal, simulated according to the rhythm of the ECG signal, is illustrated in Figure 6.

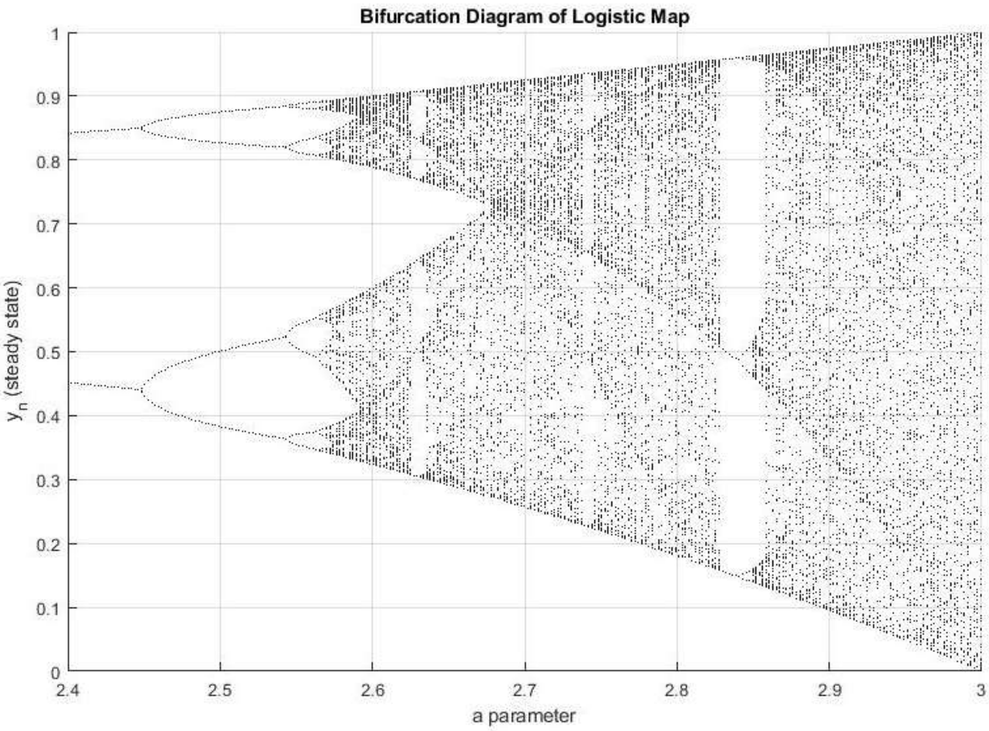

Fig. 6 EEG Bifurcation Diagram of Logistic Map

III. CONCLUSION

The simulations demonstrate the emergence of a next-generation nonlinear oscillator composed of ECG and EEG signals. Based on the obtained results, it is possible to perform unique, individual-specific encryption using such next-generation nonlinear oscillators. This is because the initial conditions and parameters of each person's heart and brain signals are inherently unique.

In future studies, nonlinear communication based directly on physical ECG and EEG signals may be realized. In such communications, unauthorized access to the transmitted data will be more difficult, as acquiring individual-specific ECG and EEG signals is inherently challenging.

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