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A New Secure Communications Scheme Based on a Chaotic Hybrid Optical Bistable System

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ABSTRACT This paper presents a novel approach for secure communication utilizing a chaotic hybrid optical bistable system and chaotic modulation. The proposed crypto system encrypts the message at the transmitter using the chaotic hybrid optical bistable system with decorrelation operation to improve the chaotic sequence's performance. The encoded message is then injected into the dynamics of the chaotic memristor system. At the receiver, the synchronization of the two chaotic systems with passive control and predictive control allows for the recovery of the message through chaotic demodulation. The effectiveness of this approach is demonstrated through numerical simulation using medical images.

KEYWORDS
Chaotic synchronization
Passive control
Predictive control
Chaos-based cryptography
Chaotic demodulation

INTRODUCTION

The idea of using chaos in communication systems was inspired by the discovery of Pecora-Carroll (Pecora and Carroll 1990) in 1990. They showed that two identical chaotic systems with different initial conditions can possibly synchronize if they are suitably coupled, that is, under certain conditions.

In communication systems, synchronization is a very important key for successful transmission Halimi *et al.* (2014); Takhi *et al.* (2021); Zouad *et al.* (2019). The role of synchronization is to try to estimate some of the states of the dynamic system or sometimes unknown inputs. This means that two chaotic signals will be said to be synchronized if they are asymptotically identical when time tends to infinity. Sensitivity to initial conditions is a fundamental characteristic of chaotic systems, which makes chaotic synchronization seem difficult to achieve and presents more constraints. In the literature, there are several synchronization methods, synchronization by impulsive control Hamiche *et al.* (2011), observer-based synchronization Bouraoui and Kemih (2013); Kemih *et al.* (2011); Hamiche *et al.* (2021) and many other approaches Nestor *et al.* (2022); Tutueva *et al.* (2022); Kemih *et al.* (2014b); Roldán-Caballero *et al.* (2023).

One of the most important engineering applications of chaos synchronization is secure communication because of the properties of random behaviors and their sensitivity to initial conditions. For the purpose of establishing secure communication, the first step is to encrypt the signal that is intended to be transmitted. Encryption refers to the process of transforming the plain text signal into an unintelligible form so that unauthorized individuals cannot decipher the message content. Once the signal has been encrypted, it is sent to the receiver through a public channel. However, due to the open nature of the channel, it is possible for hackers to intercept and steal some information. This is where various encryption and decryption mechanisms come into play.

The receiver will utilize specific decryption mechanisms to reverse the encryption process and recover the original signal Chang *et al.* (2015). In the medical field, digital images consist of multimedia data that may contain confidential information. However, the development of a secure crypto system to safeguard the medical image content is a challenging task. In reference Bouhous and Kemih (2018), a new encryption approach is suggested utilizing optical time-delay chaotic systems and wavelets for data transmission. In Mohadeszadeh and Pariz (2022), to enhance the unpredictability of the information signal, the transmitted signals to the channel are deemed to be the fractional-order derivative of the product of the information signal and the chaotic system states.

To synchronize the master and slave systems, a proper adaptive fractional-order control law is derived on the receiver side using the Lyapunov stability theorem. Similarly, in Hashemi *et al.* (2020), the authors proposed a chaotic secure communication system between the base transmitter station and mobile equipment. By applying the Lyapunov stability theory and the finite-time synchronization concept, they designed a robust terminal sliding

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mode controller. Furthermore, in Liao *et al.* (2021), the application of the Lu system to generate chaotic signals is proposed, which are then used to encrypt the biomedical information. Finally, using one of the states of the chaotic system, a simple proportional-derivative (PD) controller is designed to synchronize the master-slave chaotic systems for decrypting the biomedical information.

Motivated by the extent of previous work and on the other hand, adopting a combination-based transmission method can strengthen the security and complexity of the information transmission. In this work, we propose a novel encryption method based on a chaotic hybrid optical bistable system and chaotic modulation. In the existing results of chaos-based secure communication in literature, the transmitters are constructed with only one single chaotic system. In this paper, in order to enhance the security of the communication, we use two chaotic systems to construct the transmitter.

Our algorithm is composed of three steps: (1) encryption, (2) synchronization, and (3) extraction-decryption. The message is recovered by chaotic demodulation after synchronization of the two chaotic systems with passive control and predictive control. A numerical simulation with a medical image is provided to show the performance of the proposed approach.

The present work is structured as follows: Section 2 presents the proposed secure communications scheme, providing a brief description of the passive and predictive controllers. Section 3 details the design of the transmitter and receiver. Section 4 presents numerical simulations aimed at demonstrating the effectiveness of the proposed approach. Finally, Section 5 provides some concluding remarks.

THE PROPOSED SECURE COMMUNICATIONS SCHEME

Figure 1 summarizes the proposed secure communication scheme.

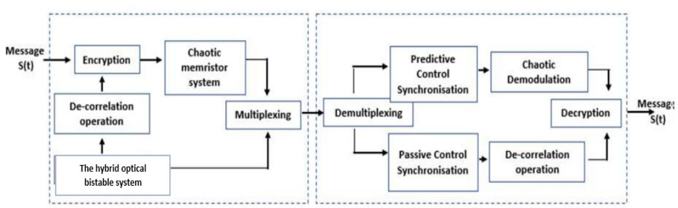

Figure 1 Proposed secure communication block diagram

Design of the Transmitter

The encryption sequence is generated using the hybrid optical bistable system Abdelouahab and Hamri (2012) at the transmitter:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ \dot{x}_3 &= -ax_3 - x_2 + bx_1(1 - x_1^2) \end{aligned} \tag{1}$$

Where :x_1, x_2 and x_3 are the three states of the system and a and b the real constants. When system parameters $a = 0.5$ and $b = 0.65$,then, the system (1) exhibits a chaotic attractor as shown in Fig.2(a)-(b).

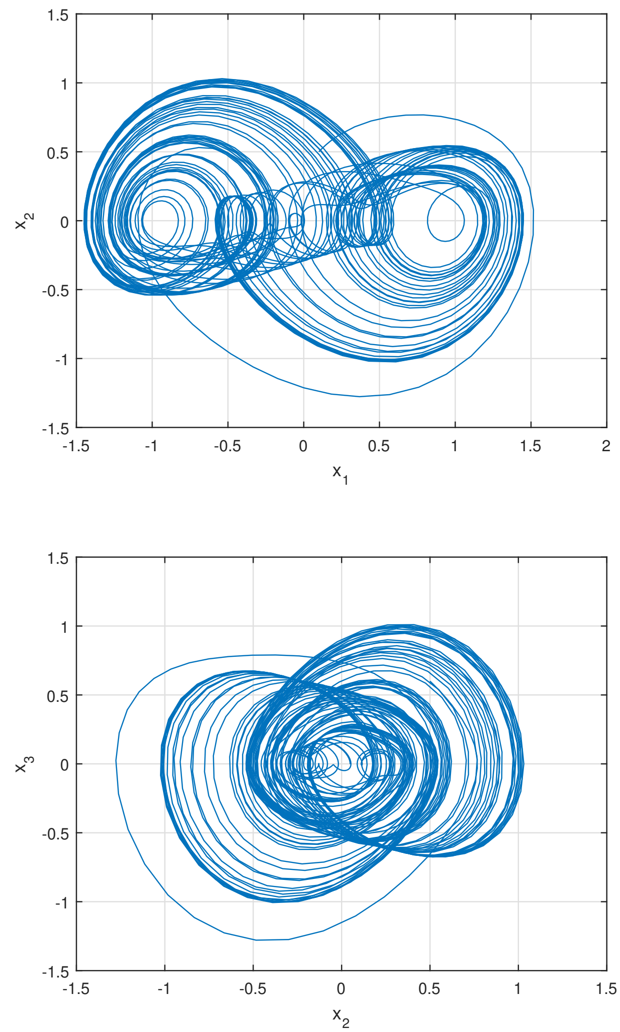

Figure 2 The phase portraits of system (1)

To optimize the performance of the chaotic sequence and its random statistical properties, the decorrelation operation was implemented using the following equations Liu *et al.* (2018):

$$S_1 = x_1 * 10^4 - floor\left(x_1{}^*10^4\right), \tag{2}$$

S_1 is the output sequence.

Fig. 3 represents an understanding between a chaotic sequence and the decorrelation result of a chaotic sequence. As we can see, this operation allows use to enhance the performance of the chaotic sequence and the random statistical properties.

The nonlinear encryption function is as follows:

$$G = 0.1 * (S_1^2 + S_1 m_t(t)) \tag{3}$$

Subsequently, the coded message is incorporated into the behavior of the chaotic memristor system for transmission and is governed by the subsequent equation Bao *et al.* (2011):

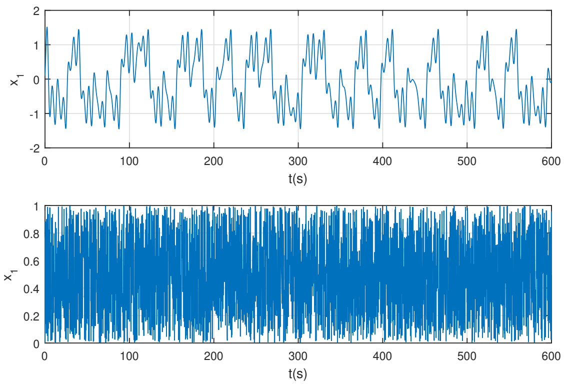

Figure 3 The chaotic sequence and the decorrelation result of chaotic sequence

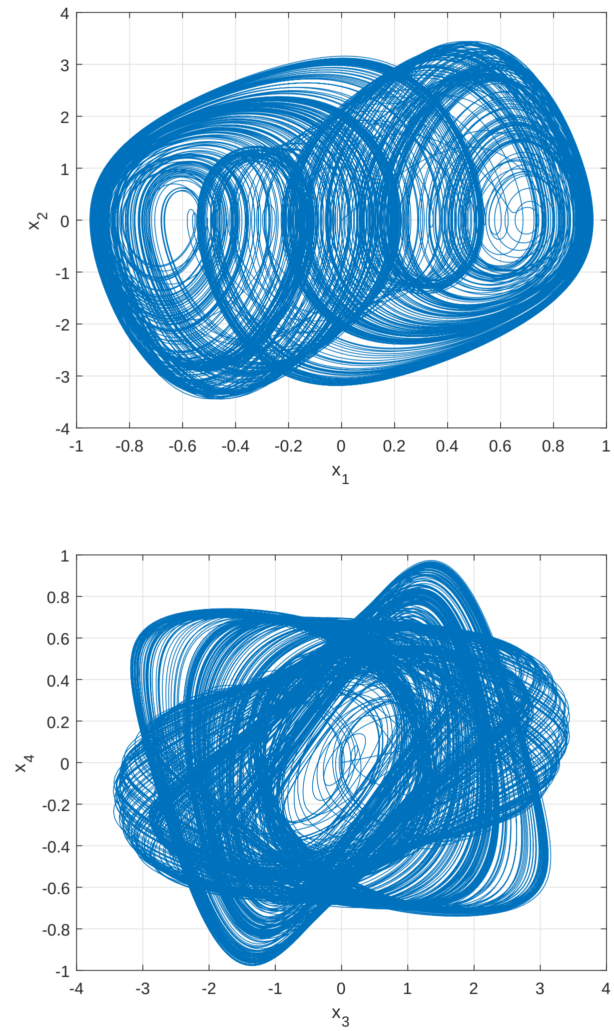

Figure 4 The phase portraits of system (4)

$$
\begin{aligned}
\dot{xx}_1 &= xx_2 + G \\
\dot{xx}_2 &= \alpha\left(xx_3 - \left(3bxx_1{}^2 - a\right)xx_2\right) \\
\dot{xx}_3 &= x_2 - \gamma xx_3 + xx_4 \\
\dot{xx}_4 &= \beta xx_3
\end{aligned}
\tag{4}
$$

where α, β, γ, a and b the real constants. When system parameters $\alpha = 21$, $\beta = 48$, $\gamma = 0.6$, $a = 1/7$, and $b = 2/7$, system (4) Manifests a chaotic attractor, as demonstrated in Fig.3(a)-(b).

Design of the receiver

The receiver is comprised of two chaotic systems that are exactly the same as the ones used in the transmitter. The primary purpose of these systems is to synchronize the signals between the transmitter and the receiver. This synchronization is crucial in order to demodulate and decrypt the received signal.

Synchronization of the chaotic The hybrid optical bistable system with passive control

Passivity based control : Considering the nonlinear system presented in the following:

$$
\begin{aligned}
\dot{x}(t) &= f(x(t), u(t)) \\
y(t) &= h(x(t))
\end{aligned}
\tag{5}
$$

$u(t)$ is the input vector and $y(t)$ is the output vector.

Definition 1 (Kemih *et al.* (2007); Yu (1999)). System (5) is said to be at " phase minimum" if the dynamic zero is asymptotically stable.

Definition 2 (Kemih *et al.* (2007); Yu (1999)). System (5) is considered passive if there exists a real constant β such that the following inequality is satisfied for all $\forall t \geq 0$:

$\int_0^t u^T(\tau)\ y(\tau) \geq \beta$ and

$$
\int_0^t u^T(\tau)\ y(\tau)\ dt + \beta \geq \int_0^t \rho y^T(\tau)\ y(\tau)\ d\tau \tag{6}
$$

The definition implies that in a passive nonlinear system, the rise in stored energy is solely attributable to an external source.

System (5) in the ordinary form Yu (1999) :

$$
\begin{aligned}
\dot{z} &= f(z) + g(z, y)\, y \\
\dot{y} &= l(z, y) + k(z, y)\, u
\end{aligned}
\tag{7}
$$

If System (5) is in the minimum phase, then the nonlinear system (7) could be treated as a passive system and stabilized asymptotically at equilibrium points through the use of closed-loop control in the form presented in references [23-24]:

$$
u = k(z, y)^{-1}\left[-l(z, y) - \frac{\partial W(z)}{\partial z} g(z) - \gamma y + \eta\right] \tag{8}
$$

Where $W(z)$ is Lyapunov's function of $f_0(z)$, γ is a positive value and η is an external signal connected to the reference input.

Synchronization of the chaotic hybrid optical bistable system by passive control: In this section, we will utilize the passive command to synchronize the chaotic hybrid optical bistable system. The equation (1) represents the master system, and the slave system is described as:

$$\begin{aligned} \dot{p}_1 &= p_2 + u_1 \\ \dot{p}_2 &= p_3 + u_2 \\ \dot{p}_3 &= -ap_3 - p_2 + bp_1(1 - p_1^2) \end{aligned} \tag{9}$$

we assume that the error is:

$$e = (e_1, e_2, e_3)^T = (p_1 - x_1, p_2 - x_2, p_3 - x_3)^T \tag{10}$$

We get the equations for the synchronization error, as follows:

$$\begin{aligned} \dot{e}_1 &= e_2 + u_1 \\ \dot{e}_2 &= e_3 + u_2 \\ \dot{e}_3 &= -ae_3 - e_2 + bp_1(1 - p_1^2) - bx_1(1 - x_1^2) \end{aligned} \tag{11}$$

after simplification, we get:

$$\begin{aligned} \dot{e}_1 &= e_2 + u_1 \\ \dot{e}_2 &= e_3 + u_2 \\ \dot{e}_3 &= -ae_3 - e_2 + be_1 - be_1^3 - 3be_1^2x_1 - 3be_1x_1^2 \end{aligned} \tag{12}$$

We start by rewriting the system in the form of a passive system (7), for that, we choose: $z_1 = e_3, y_1 = e_1, y_2 = e_2$.

Which allows us to get: $[f(z) = [-az_1], g(z, y) = [b - by_1^2 - 3by_1x_1 - 3by_1^2, -1], l(z, y) = [y_2, z_1]^T, k(z, y) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

We take:

$$V(z, y) = W(z) + \tfrac{1}{2}y_1^2 + \tfrac{1}{2}y_2^2 \tag{13}$$

Where $W(z)$ is a Lyapunov function, with $W(0) = 0$:

$$W(z) = \tfrac{1}{2}z_1^2 \tag{14}$$

The calculation of the derivative of the Lyapunov function as a function of time is as follows:

$$\frac{dW(z)}{dt} = -az_1^2 \leq 0.$$

The dynamic zero of the synchronization error is stable in the sense of Lyapunov. The derivative $\frac{dW(z)}{dt}$ along the dynamics of the error system (12) is given as follows :

$$\frac{dV(z, y)}{dt} = \frac{\partial W(z)}{\partial z} \times \dot{z} + y \times \dot{y}$$

$$= \tfrac{\partial W(z)}{\partial z} f(z) + \tfrac{\partial W(z)}{\partial z} g(z, y)y + l(z, y)y + k(z, y)uy \tag{15}$$

Since :

$$\tfrac{dW(z)}{dz} f(z) \leq 0 \tag{16}$$

Then equation (15) becomes:

$$\tfrac{dV(z,y)}{dt} \leq \tfrac{\partial W(z)}{\partial z} g(z, g)y + (l(z, y) + k(z, y)u)y \tag{17}$$

Closed-loop control is selected in the form :

$$u = k^{-1}(z, y)\left[-l(z, y) - \frac{\partial W(z)}{\partial z} g(z, y) - \gamma y + v\right] \tag{18}$$

If we consider (18), we find :

$$u = \begin{bmatrix} -e_2 - be_3 + by_1^2e_3 + 3by_1x_1e_3 + 3by_1^2e_3 - \gamma e_1 \\ -\gamma e_2 \end{bmatrix} \tag{19}$$

Where γ is a positive constant. When substituting (18) into (17), we get:

$$\frac{\partial V(z, y)}{\partial t} \leq -\gamma y^2 + vy \tag{20}$$

Integrating (20) gives us:

$$V(z, y) - V(z_0, y_0) \leq \int_0^t -\gamma y^2(\tau)d\tau + \int_0^t v(\tau)y(\tau)d\tau \tag{21}$$

$V(z, y) \geq 0$ and $\rho = V(z_0, y_0)$

$$\int_0^t v(\tau)y(\tau)d\tau + \rho \geq V(z, y) + \int_0^t \gamma y^2(\tau)d\tau \geq V(z, y) \tag{22}$$

The relation (22) satisfies the definition of passivity given by the equation (6), so the synchronization error system (12) is strictly passive.

The error synchronization for all states is plotted in Fig. 5. We see that the state estimation effect is satisfactory.

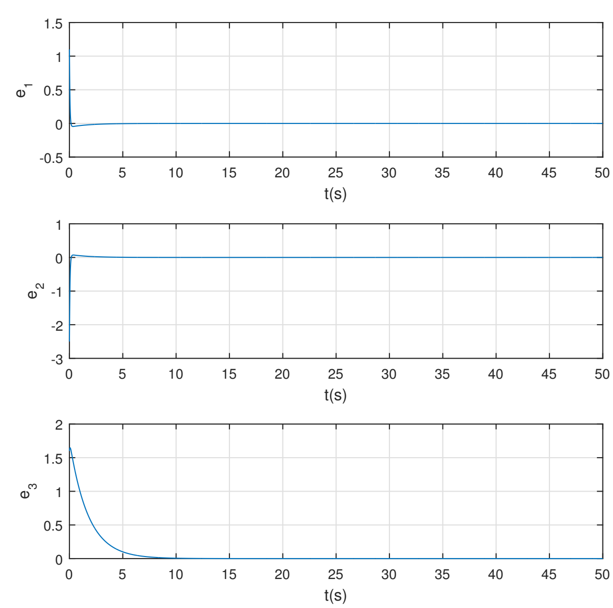

Figure 5 The synchronization error results between the chaotic hybrid optical bistable system transmitter/receiver

Predictive control: The controlled nonlinear system, in which chaos is to be suppressed, is represented as:

$$\dot{x}(t) = f_1(x(t)) + u_1(t) \tag{23}$$

The aim of predictive feedback control is to achieve asymptotic convergence of the system to either a stable fixed point or an unstable periodic orbit x_f

The fixed point or equilibrium point of the system (23) is the point x_f such as:

$$\frac{dx}{dt} = \dot{x} = f_1\left(x_f\right) = 0 \tag{24}$$

As part of predictive control, the command form $u_1(t)$ is chosen as the following form Messadi *et al.* (2015); Boukabou *et al.* (2008); Messadi and Mellit (2017); Wang and Wang (2003) :

$$u_1(t) = K(x_p(t) - x(t)) \tag{25}$$

Where : K represents the gain and $x_p(t)$ Represents the predicted state.

By making a one-step prediction ahead, we get:

$$u_1(t) = K(\dot{x}(t) - x(t)) \tag{26}$$

Synchronization of the chaotic memristor system by the predictive control We will apply predictive control to synchronize the chaotic memristor system. The master system is described by equation (4) and the slave system is:

$$\begin{aligned}
\dot{yy}_1 &= yy_2 + u_1 \\
\dot{yy}_2 &= \alpha(yy_3 - [yy_3 - (3byy_1{}^2 - a)yy_2] + u_2 \\
\dot{yy}_3 &= yy_2 - \gamma yy_3 + yy_4 + u_3 \\
\dot{yy}_4 &= -\beta yy_3 + u_4
\end{aligned} \tag{27}$$

The system is asymptotically synchronized in the sense that: $\lim_{t\to\infty} e(t) \to 0$

First of all, we start by calculating the error between the transmitter / receiver systems :

$[ee_1\ ee_2\ ee_3\ ee_4]^T = [yy_1 - xx_1\ yy_2 - xx_2\ yy_3 - xx_3\ yy_4 - xx_4]^T$

$$\begin{aligned}
\dot{ee}_1 &= ee_2 + u_1 \\
\dot{ee}_2 &= \alpha[ee_3 - \ (3byy_1{}^2 - a)yy_2 + (3bxx_1{}^2 - a)xx_2] + u_2 \\
\dot{ee}_3 &= ee_2 - \gamma ee_3 + ee_4 + u_3 \\
\dot{ee}_4 &= -\beta ee_3 + u_4
\end{aligned} \tag{28}$$

Based on equations (26), (28) and applying the LMIs we obtain the value of the matrix K as follows:

$$K = \begin{bmatrix} 4.7238 & -1 & -1 & -2.3619 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 9 \end{bmatrix} \tag{29}$$

And the command will have the following formula:

$$u_1\,(t) = K\,(\dot{ee}\,(t) - ee\,(t))$$

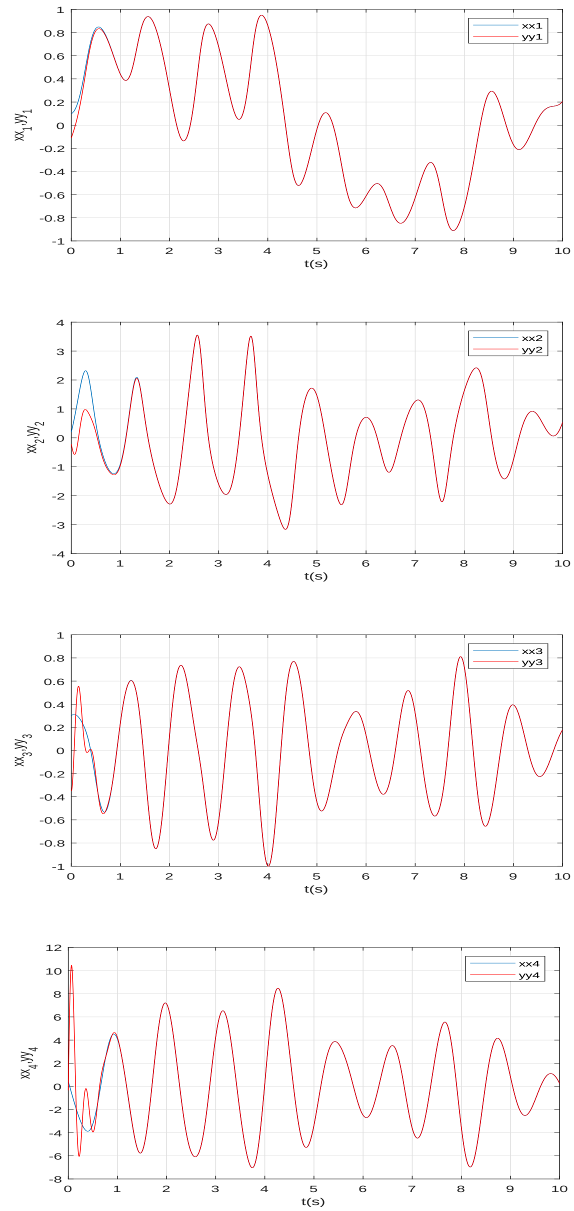

Figure 6 The synchronization results between the chaotic memristor transmitter/receiver

The chaotic 4D Memristor synchronization for all states is plotted in Fig. 5. We see that the state estimation effect is satisfactory.

To restore the message transmitted by inclusion at the receiver, we will use chaotic demodulation Wang and Wang (2003).

$$\begin{cases} \frac{dQ}{dt} = -\xi K \left(yy_1 + \xi \hat{G}\,(t) \right) \\ \hat{G}\,(t) = \xi K xx_1\,(t) + Q \end{cases} \tag{30}$$

$\widehat{G}\,(t)$ the reconstructed signal

to decrypt the reconstructed signal, we use the following nonlinear function : $\widehat{m_r}(t) = (\widehat{G}(t) - \widehat{SS}^2(t))/\widehat{SS}(t)$ where $SS(t) = y_1(t) * 10^4 - floor\left(y_1(t)^* 10^4\right)$

To show the effectiveness of the proposed encryption system. we will first transmit a square signal of frequency f = 30 Hz. The

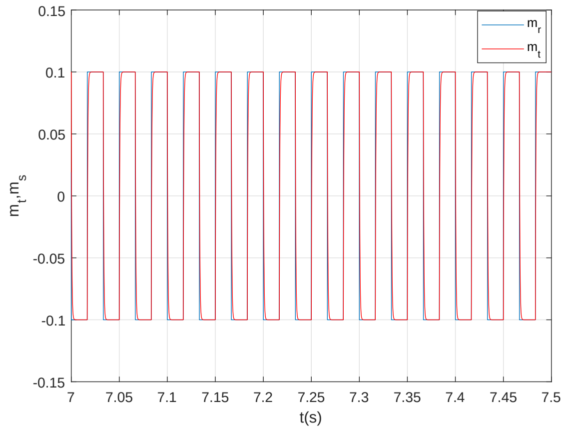

Figure 7 The transmitted message and the reconstructed message

performance of the proposed approach is shown in Fig. 6. As it can be seen in Fig 7, the original and recovered messages are nearly the same.

In the field of medicine, digital images are considered multimedia data that often contains confidential and sensitive information. Due to the highly sensitive nature of such information, it is imperative to protect digital medical images with a robust crypto system that can prevent unauthorized access or misuse. However, designing an effective crypto system that can safeguard medical image content poses a significant challenge due to the complexity and variety of medical imaging modalities. One of the alternatives to solving this problem is the approach proposed in this article. Fig. 8.a shows the original version of the medical image. Fig. 8.b shows the encrypted image, and Fig. 8.c shows the received and decrypted images. These simulation results demonstrate the feasibility of a secure communication strategy for the transmission of medical images.

CONCLUSION

In this study, we have put forward a new method for secure communication that relies on hybrid chaotic synchronization and chaotic modulation. The fundamental principle of the suggested method is straightforward: at the transmitter end, two chaotic systems are utilized to boost the security of communication. Specifically, the message is encrypted using the chaotic hybrid optical bistable system, and then the encoded message is incorporated into the dynamics of the chaotic memristor system. At the receiver end, the message is retrieved by means of chaotic demodulation after synchronization of the two chaotic systems with passive control and predictive control. To illustrate the efficacy of this approach, two examples have been presented, one based on a square signal and the other on medical imagery.

Availability of data and material

Not applicable.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

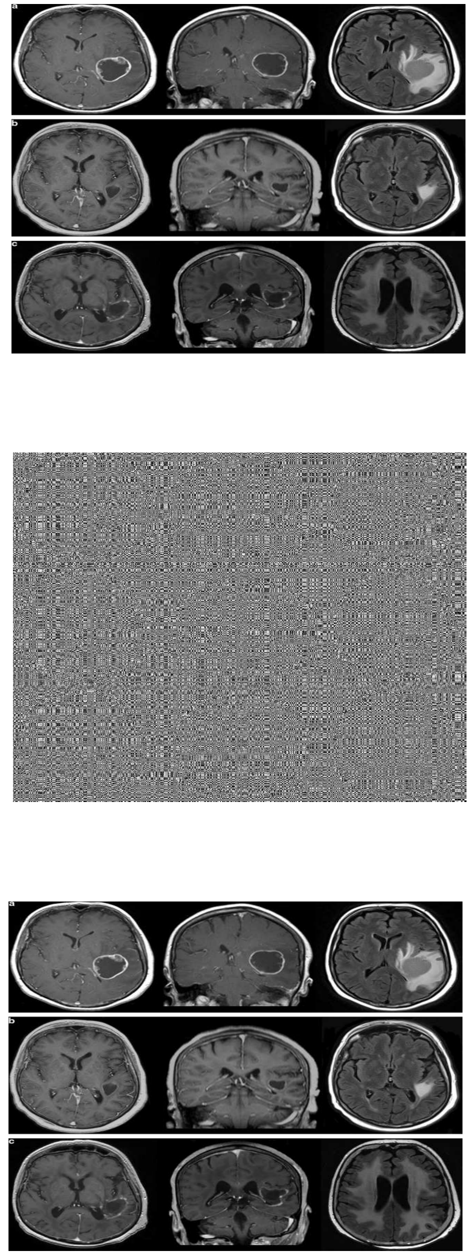

Figure 8 The original, transmitted and decrypted images (respectively)

Ethical standard

The authors have no relevant financial or non-financial interests to disclose.

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