

Encrypted audio communication based on synchronized unified chaotic systems

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Abstract—In this paper, encrypted audio communications based on synchronization of coupled unified chaotic systems in master-slave configuration is numerically studied. We transmit the encrypted audio messages by using two unsecure channels. Encoding, transmission, and decoding audio messages in chaotic communication is presented.

Keywords—Audio Encrypted, Chaos, Synchronization

I. INTRODUCTION

During the last decades, synchronization of two coupled chaotic systems has received great attention from mathematicians, physicists, biologists, control engineers, etc. see e.g. [1]-[7]. This interest has been greatly motivated by the possibility of encrypted information transmission by using a chaotic carrier, see e.g. [4, 8-14].

Based on chaos synchronization of two unified systems reported in [15], the aim of this paper is to study the encrypted audio transmission. In particular, this objective is achieved by synchronizing the unified chaotic systems via Generalized Hamiltonian forms and observer design proposed in [5]. Recently, was shown in [15] that the mentioned approach is indeed suitable to synchronize two coupled unified chaotic systems in master-slave configuration. In this work, we transmit encrypted audio messages via insecure channels between two remote points.

The present study shows the encrypted and recovery of audio messages by using two unified systems. In particular, when Lorenz-Lorenz, Chen-Chen, and Lü-Lü chaotic systems are operated.

The remainder of this paper is organized as follows: In Section II, the system communication description is given. In Section III, the model of the unified chaotic system is described. Section IV presents the synchronization of two unified chaotic systems by using Hamiltonian forms and observer approach. In Section V, encrypted audio transmission is shown. The paper is concluded with some remarks in Section VI.

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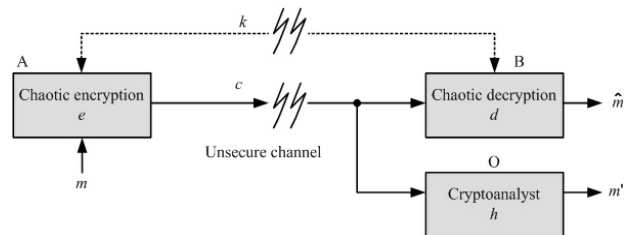


Fig. 1. Chaotic cryptosystem for audio communication.

II. SYSTEM COMMUNICATION DESCRIPTION

In this section, a cryptosystem based on synchronized chaotic systems is described. The aim is to transmit encrypted audio messages from transmitter A to remote receiver B as is depicted in Fig. 1. An audio message m is to be transmitted over an insecure communication channel. To avoid any unauthorized receiver (intruder O) located at the mentioned channel; m is encrypted prior to transmission to generate an encrypted message c ,

$$c = e(m, k),$$

by using a chaotic system e on transmitter A.

The encrypted message c is sent to receiver B, where m is recovered as \hat{m} from the chaotic decryption d , as

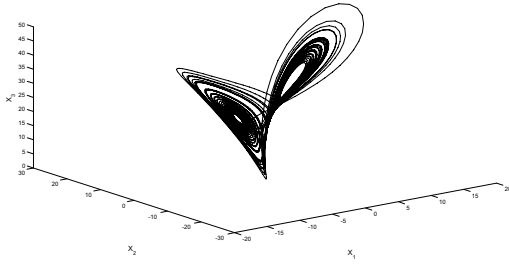
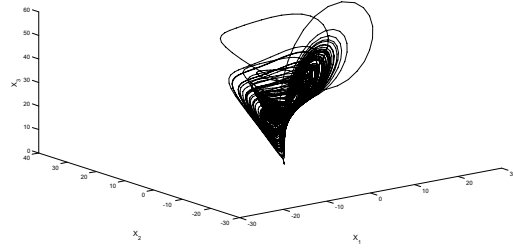
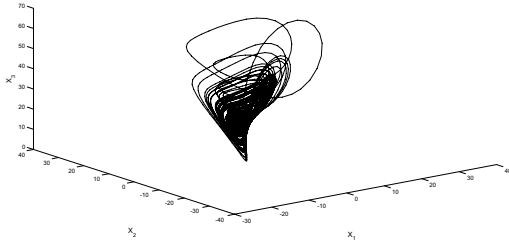
$$\hat{m} = d(c, k).$$

If e and d have used the same key k , then at receiver end B it is possible to obtain $\hat{m} = m$. A secure channel (dashed line) is used for transmission of the keys, k . Generally, this secure communication channel is a courier and is too slow for the transmission of m . Our chaotic cryptosystem is reliable, if it preserves the security of m , i.e. if $m' \neq m$ for even the best cryptanalytic function h , given by

$$m' = h(c).$$

To achieve the proposed chaotic encryption scheme, we appeal to unified chaotic system for encryption/decryption purposes (c and d , respectively).

The unified chaotic system have a number of parameters determining their dynamics; such parameters and initial conditions are the coding “keys”, k . We expect that it can perform the objective of the secure communication and the transmitting audio messages can be recovered at the receiver B. In order to guarantee the encryption and decryption, the unified chaotic systems have to achieve the so-called synchronization on both chaotic transmitter A and receiver B.


 Fig. 2. Lorenz attractor projected onto the (x_1, x_2, x_3) -space.

 Fig. 4. Lü attractor projected onto the (x_1, x_2, x_3) -space.

 Fig. 3. Chen attractor projected onto the (x_1, x_2, x_3) -space.

III. UNIFIED CHAOTIC SYSTEM

Consider the unified chaotic system [16], described by

$$\begin{aligned} \dot{x}_1 &= (25\alpha + 10)(x_2 - x_1), \\ \dot{x}_2 &= (28 - 35\alpha)x_1 - x_1x_3 + (29\alpha - 1)x_2, \\ \dot{x}_3 &= x_1x_2 - \left(\frac{\alpha + 8}{3}\right)x_3, \end{aligned} \quad (1)$$

where the parameter $\alpha \in [0, 1]$, for the whole interval the unified system is chaotic. Obviously, when $\alpha = 0$ the system (1) is the original Lorenz system [17]. While for $\alpha = 1$ the system (1) is the original Chen system [18]. For $\alpha = 4/5$ the system (1) corresponds to the critical (Lü) system [19]. In fact, the system (1) bridges the gap between the Lorenz and Chen systems [16].

By using the initial conditions $x(0) = (0.1, 0.1, 0.01)$, Figs. 2, 3, and 4 show the chaotic attractors of Lorenz, Chen, and Lü respectively, projected onto (x_1, x_2, x_3) -space.

IV. SYNCHRONIZATION OF TWO UNIFIED CHAOTIC SYSTEMS

Considering the following chaotic system described by the state equation

$$\dot{x} = f(x), \quad (2)$$

where $x \in \mathbb{R}^n$ is the state vector, $f: \mathbb{R}^n \rightarrow \mathbb{R}^n$ is a nonlinear function. In [5] was reported how the chaotic system (2) can be rewritten in the following Generalized Hamiltonian canonical form,

$$\dot{x} = \mathcal{J}(x) \frac{\partial H}{\partial x} + \mathcal{S}(x) \frac{\partial H}{\partial x} + \mathcal{F}(x), \quad x \in \mathbb{R}^n. \quad (3)$$

In addition, in the context of observer design, we consider a special class of Generalized Hamiltonian forms with linear output map y , given by

$$\begin{aligned} \dot{x} &= \mathcal{J}(y) \frac{\partial H}{\partial x} + (\mathcal{I} + \mathcal{S}) \frac{\partial H}{\partial x} + \mathcal{F}(y), \quad x \in \mathbb{R}^n, \\ y &= \mathcal{C} \frac{\partial H}{\partial x}, \quad y \in \mathbb{R}^m. \end{aligned} \quad (4)$$

Denoting the estimate of the state x by ξ , and considering the Hamiltonian energy function $H(\xi)$ to be the particularization of H in terms of ξ . Similarly, we denote by η the estimated output, computed in terms of the estimated state ξ .

A nonlinear state observer for the special class of Generalized Hamiltonian form (4) is given by

$$\begin{aligned} \dot{\xi} &= \mathcal{J}(y) \frac{\partial H}{\partial \xi} + (\mathcal{I} + \mathcal{S}) \frac{\partial H}{\partial \xi} + \mathcal{F}(y) + K(y - \eta), \\ \eta &= \mathcal{C} \frac{\partial H}{\partial \xi}, \quad \eta \in \mathbb{R}^m, \end{aligned} \quad (5)$$

with $\xi \in \mathbb{R}^n$ and K is the observer gain.

The state estimation error, defined as $e = x - \xi$ and the output estimation error, defined as $e_y = y - \eta$, are governed by

$$\begin{aligned} \dot{e} &= \mathcal{J}(y) \frac{\partial H}{\partial e} + (\mathcal{I} + \mathcal{S} - KC) \frac{\partial H}{\partial e}, \quad e \in \mathbb{R}^n, \\ e_y &= \mathcal{C} \frac{\partial H}{\partial e}, \quad e_y \in \mathbb{R}^m. \end{aligned} \quad (6)$$

Definition 1 (Chaotic synchronization) [7]. The slave system (5) (nonlinear state observer) synchronizes with the chaotic master system in the special class of Generalized Hamiltonian form (4), if

$$\lim_{t \rightarrow \infty} \|x(t) - \xi(t)\| = 0, \quad (7)$$

no matter which initial conditions $x(0)$ and $\xi(0)$ have. Where the state estimation error $e(t) = x(t) - \xi(t)$ represents the synchronization error.

In the sequel, we synchronize two unified chaotic systems (1) in master-slave configuration (see Fig. 5), via Generalized Hamiltonian forms and observer design proposed in [5]. Firstly, we rewrite the unified system (1) in Hamiltonian form as the master system and design a state observer for (1) like the slave system, as follows. Taking as Hamiltonian energy function to

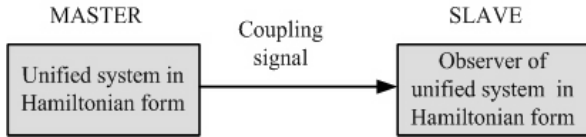


Fig. 5. Master-slave synchronization scheme.

$$H(x) = \frac{1}{2} (x_1^2 + x_2^2 + x_3^2) \quad (8)$$

and gradient vector as

$$\frac{\partial H}{\partial x} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}. \quad (9)$$

The unified system (1) in Hamiltonian form according to Eq. (4) (as master system) is given by

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 30\alpha - 9 & 0 \\ -(30\alpha - 9) & 0 & -x_1 \\ 0 & x_1 & 0 \end{bmatrix} \frac{\partial H}{\partial x} \quad (10) \\ + \begin{bmatrix} -(25\alpha + 10) & -5\alpha + 19 & 0 \\ -5\alpha + 19 & 29\alpha - 1 & 0 \\ 0 & 0 & -\frac{(\alpha+8)}{3} \end{bmatrix} \frac{\partial H}{\partial x}.$$

The output signal to be transmitted to slave system is $y = [1 \ 0 \ 0] \partial H / \partial x = x_1$. The matrices \mathcal{C} , \mathcal{S} , and \mathcal{I} , are given by

$$\mathcal{C} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}, \\ \mathcal{S} = \begin{bmatrix} -(25\alpha + 10) & -5\alpha + 19 & 0 \\ -5\alpha + 19 & 29\alpha - 1 & 0 \\ 0 & 0 & -\frac{(\alpha+8)}{3} \end{bmatrix}, \\ \mathcal{I} = \begin{bmatrix} 0 & 30\alpha - 9 & 0 \\ -(30\alpha - 9) & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

In [15] was shown that the pair of matrices $(\mathcal{C}, \mathcal{S})$ constitutes a pair detectable, but non observable. Thus, it is possible to design an observer for master system (10) (as slave system) according to Eq. (5), is as follows

$$\begin{bmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \\ \dot{\xi}_3 \end{bmatrix} = \begin{bmatrix} 0 & 30\alpha - 9 & 0 \\ -(30\alpha - 9) & 0 & -y \\ 0 & y & 0 \end{bmatrix} \frac{\partial H}{\partial \xi} \quad (11) \\ + \begin{bmatrix} -(25\alpha + 10) & -5\alpha + 19 & 0 \\ -5\alpha + 19 & 29\alpha - 1 & 0 \\ 0 & 0 & -\frac{(\alpha+8)}{3} \end{bmatrix} \frac{\partial H}{\partial \xi} \\ + \begin{bmatrix} k_1 \\ k_2 \\ k_3 \end{bmatrix} e_1, \\ \eta = \xi_1,$$

where the synchronization error is defined as $e_1 = y - \eta$. From (10) and (11) the synchronization error dynamics is governed by

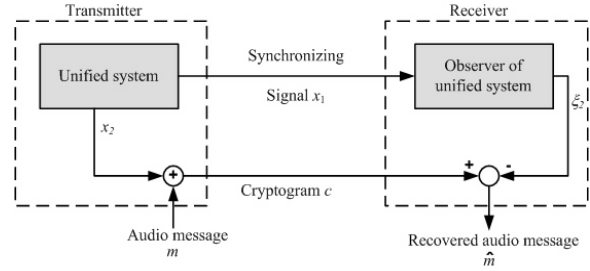


Fig. 6. Audio communication scheme

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} 0 & 30\alpha - 9 & 0 \\ -(30\alpha - 9) & 0 & -y \\ 0 & y & 0 \end{bmatrix} \frac{\partial H}{\partial e} \quad (12) \\ + \begin{bmatrix} -(25\alpha + 10) & -5\alpha + 19 & 0 \\ -5\alpha + 19 & 29\alpha - 1 & 0 \\ 0 & 0 & \frac{(\alpha+8)}{3} \end{bmatrix} \frac{\partial H}{\partial e}.$$

In [15] was given the stability conditions which guarantees asymptotic stability to zero of $e(t)$ Eq. (12). Based on the mentioned conditions, we have selected $k_1 = 11$, $k_2 = 50$, and $k_3 = 32$ which guarantee the convergence of the synchronization error Eq. (12) to zero.

V. ENCRYPTED AUDIO COMMUNICATION

In this section, we describe the communication system based on synchronized chaos. Fig. 6 shows a block diagram to transmit secret audio messages by chaotic additive masking technique. We will use the unified system (1) as chaos generator. With this scheme, we obtain faster synchronization and higher privacy; one channel is used to send the chaotic synchronizing signal $x_1(t)$ from the transmitter (10), with no connection with the secret audio message $m(t)$. While the other channel is used to transmit hidden message $m(t)$ which is recovered at the receiver end by means of the comparison between the signals $x_2(t) + m(t)$ and $\xi_2(t)$. Figure 6 shows the chaotic secure communication system with two transmission channels.

In this final part, via numerical simulations, we illustrate the encrypted audio transmission. We use as transmitter and receiver the unified chaotic system given in (1), for different values of parameter α , i.e. for Lorenz ($\alpha = 0$), Chen system ($\alpha = 1$), and Lü chaotic system ($\alpha = 4/5$), and for initial conditions $x(0) = (0.25, 0.3, 0.15)$ and $\xi(0) = (0.1, 0.2, 0.25)$. The format of the audio signal $m(t)$ is PCM 22.05 KHz, 16 Bits, monofonic channel. The mentioned audio message $m(t)$ is to be encrypted and transmitted to the receiver.

Fig. 7 shows audio communication via Lorenz-Lorenz systems ($\alpha = 0$). Original audio message $m(t)$ to be encrypted and transmitted (top of figure), transmitted chaotic signal $c(t) = x_2(t) + m(t)$ (middle of figure), and recovered audio message $\hat{m}(t)$ (bottom of figure).

Fig. 8 shows audio communication by using Chen-Chen systems ($\alpha = 1$). Original audio message $m(t)$ to be encrypted

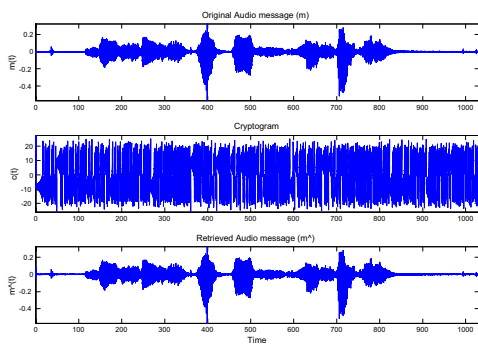


Fig. 7. Encrypted audio communication by using Lorenz-Lorenz systems.

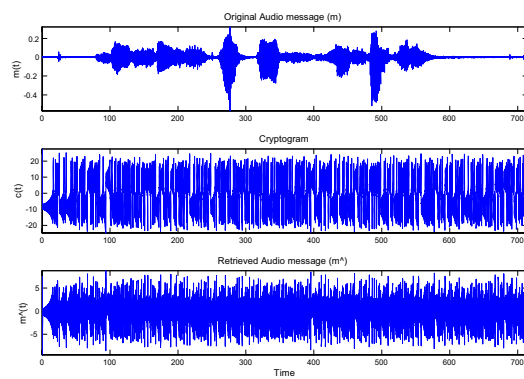


Fig. 10. Lorenz systems as transmitter and Chen systems as receiver.

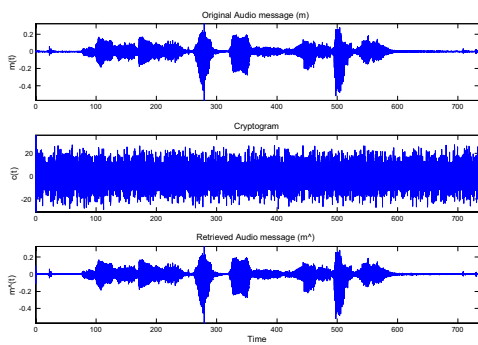


Fig. 8. Encrypted audio communication by using Chen-Chen systems.

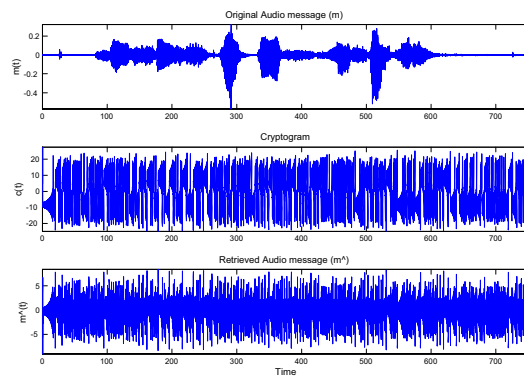


Fig. 11. Lorenz system as transmitter and Lü system as receiver.

and transmitted (top of figure), transmitted chaotic signal $c(t) = x_2(t) + m(t)$ (middle of figure), and recovered audio message $\hat{m}(t)$ (bottom of figure).

Fig. 9 shows audio communication by using Lü-Lü systems ($\alpha = 4/5$). Original audio message $m(t)$ to be encrypted and transmitted (top of figure), transmitted chaotic signal $c(t) = x_2(t) + m(t)$ (middle of figure), and recovered audio message $\hat{m}(t)$ (bottom of figure).

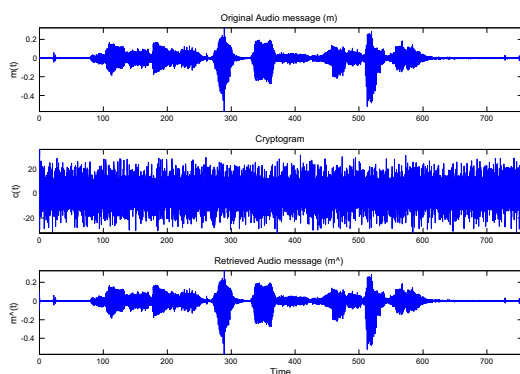


Fig. 9. Encrypted audio communication by using Lü-Lü systems.

Fig. 10 shows audio communication by using Lorenz system as transmitter and the Chen system as receiver. Original audio message $m(t)$ to be encrypted and transmitted (top of figure), transmitted chaotic signal $c(t) = x_2(t) + m(t)$ (middle of figure), and recovered audio message $\hat{m}(t)$ (bottom of figure).

Fig. 11 shows audio communication by using the Lorenz system as transmitter and Lü system as receiver. Original audio message $m(t)$ to be encrypted and transmitted (top of figure), transmitted chaotic signal $c(t) = x_2(t) + m(t)$ (middle of figure), and recovered audio message $\hat{m}(t)$ (bottom of figure).

Fig. 12 shows Lü system as transmitter and Chen system as receiver. Original audio message $m(t)$ to be encrypted and transmitted (top of figure), transmitted chaotic signal $c(t) = x_2(t) + m(t)$ (middle of figure), and recovered audio message $\hat{m}(t)$ (bottom of figure).

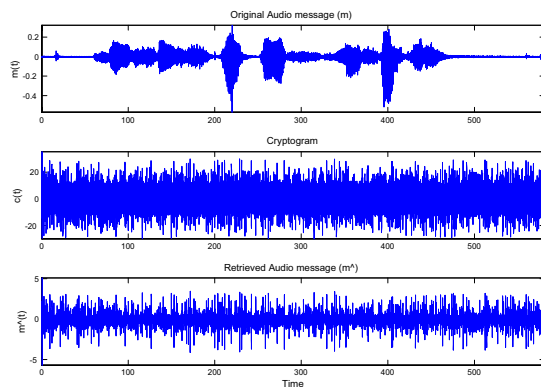


Fig. 12. Lü system as transmitter and Chen system as receiver.

Table1 the parameter value of α

Amount of points of the time serie	Lyapunov Exponent when $\alpha = 0$, (Lorenz)	Lyapunov Exponent when $\alpha = 1$, (Chen)	Lyapunov Exponent when $\alpha = \frac{4}{5}$, (Lü)
60	0.0945573	0.0879170	0.0796389
100	0.0748100	0.075035	0.0692077
200	0.0358591	0.0471714	0.0511361
300	0.0398915	0.0556478	0.0529470
400	0.0334249	0.0608744	0.0558300
500	0.0297847	0.0573976	0.0548063
1,000	0.0268131	0.0572383	0.0630120
1,500	0.0335971	0.0554648	0.0605263
10,000	0.0487245	0.0514397	0.0552146
20,000	0.0480081	0.0494818	0.0548698

Remark 1. From Figs. 7, 8, and 9, we can see that the original audio message can be faithfully recovered by the receiver. Nevertheless, the level of encryption security depends of the selected system, i.e. the parameter value of α , which is determined by the calculation of the Lyapunov exponents, see Table 1.

In Table 1 are shown the Lyapunov exponents from time series of the transmitted chaotic signals $c = x_2 + m$, which are obtained from chaotic systems Lorenz ($\alpha = 0$), Chen system ($\alpha = 1$), and Lü system ($\alpha = 4/5$), which are always chaotic.

Remark 2. From Figs. 10, 11, and 12, we can see that is not possible to recover the original audio message at the receiver; In general, if the systems in transmitter and receiver are different. Nevertheless, for the particular case when Lü-Chen (or Chen-Lü) are selected, see Fig. 12, there exist some "vestiges" (or components) of the original audio message, which means that under some proofs of spectral analysis, filtering stage, etc. the original audio message could be recovered. This issue will be studied in future work. In addition, a complete analysis on the sensibility of the initial condition used as "keys" for the encryption.

VI. CONCLUSIONS

In this paper, we have presented the transmission of encrypted audio messages based on synchronization of unified chaotic systems. This work have shown that the proposed chaotic communication schemes show a great potential for actual encryption communication systems in which the encoding is required to be secure. In a forthcoming article we will be concerned with a physical implementation of the synchronization of two chaotic unified systems in master-slave configuration, and its application to private communication of audio transmission in a network of users.

ACKNOWLEDGMENTS

The authors would like to thank to CONACYT, México under Research Grants No. J-49593-Y, No. P-50051-Y and by UABC, México, under Program No. 471, and 472, 14va Convocatoria.

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