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A Secure Communication System of Synchronized Chua's Circuits in LC Parallel Coupling

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ABSTRACT Synchronization capability of two identical chaotic systems can be used for constructing the secure communication systems where the chaotic signal is used as the information carrier. In this paper, a secure communication system is designed by using the bi-directionally synchronized identical Chua's circuits in LC parallel coupling. LC parallel circuit is used as the new coupling element instead of using a single resistor or capacitor or inductor as the coupling element. This makes the complete synchronization of Chua's circuits possible for many different sets of coupling inductance and capacitance values so that the flexibility of constructing the secure communication systems is realized. Both the synchronized Chua's circuits in LC parallel coupling and the corresponding secure communication system are constructed by using the LTspice software. The simulation results show that the secure communication system proposed in the present paper is very efficient for the message transmission for different pairs of coupling inductance and coupling capacitance values where the complete synchronization of Chua's circuits is observed occur. The two essential properties of an ideal secure communication system - perfect message masking and recovery are observed when compared to other secure communication systems already proposed and constructed previously. So, the simulation results of the present study can be used for practically constructing the efficient communication systems in future.

KEYWORDS
Chua's circuit
Chaotic masking
Secure communication system
LC parallel coupling
Complete synchronization
LTspice.

INTRODUCTION

Chaotic systems in nature are very important because of their unusual properties. The Chua's circuit is an example of chaotic systems with rich chaotic properties (Zhong and Ayrom 1985; Chua 1992) .This circuit consists of three linear energy storage elements - one inductor, two capacitors, one linear resistor and one non-linear resistor. The nonlinear resistor can be constructed in several ways. However, for the practical implementation, this can be conveniently constructed in Kennedy's implementation by using the two identical op-amps like TL082 and six resistors. The synchronization of chaotic systems is an important property as it shows some cooperative nature within the chaotic realm of the system.Furthermore, the synchronized chaotic systems can be used for some important applications in the secure communication systems.

The synchronization of two Chua's circuits in linear coupling with a resistor, capacitor and inductor is already studied by the number of researchers (Leon O.Chua and Itoh 1992; V.V.Astakhov and V.S.Anishchenko 1997; Zhilong Liu and Zhang 2019; Yao *et al.* 2019; Zhang and Wang 2023) . So, there is the scope for using some combinations of such simple coupling devices as the coupling elements between the two Chua's circuits. This is very important not only to observe the nature of chaos in the synchronization transition but also to know the possibility of complete synchronization for the various sets of parameter values. Such flexibility of using various sets of parameter values for the complete synchronization is observed in the simulations when compared to the results of previous studies with any single coupling element.

There are several methods for design and construction of the chaos based communication systems. The important methods are chaotic masking, chaotic modulation and chaotic switching (H.Dedieu and M.Hasler 1993; Ogorzalek 1993; Koh and Ushio

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1997) . In the chaotic masking method,the analogue message signal is added to a strong chaotic signal (L. Kocarev and Parlitz 1992; Cuomo and Oppenheim 1993; K.M. Cuomo and Strogatz 1993; Wu and Chua 1993; I.P. Marino and Grebogi 1999; Adel Ouannas and Luong 2021; Bonny T. *et al.* 2023) .In chaotic modulation method, the analogue message signal is modulated by the chaotic signal whereas in chaotic switching method, the digital message signals are modulated by the chaotic attractors.

The main problem of the study is to construct a secure communication system based on the chaotic masking method where the two completely synchronized chaotic systems are necessary. The chaotic masking is the very fundamental method for building any secure communication system.The masking of the message signals can be realized by using the two completely synchronized chaotic systems -with one system acting as a transmitter while the other system acting as a receiver. The required complete synchronization can be realized by using either the uni-directionally or bi-directionally coupled chaotic systems. In bi-directional or mutual coupling, the two chaotic systems will influence each other whereas in uni-directional coupling only one system will influence the other. In this study, a bi-directional coupling of two identical Chua's circuits is used for achieving the complete synchronization.

Trejo-Guerra et al. experimentally implemented the secure chaotic communication system by using the uni-directionally coupled Chua's oscillators built with the commercially available positive-type second generation current conveyor CCII+ (Trejo-Guerra and Sanchez-Lopez 2009) .The uni-directionally synchronized Chua's circuits in secure communication systems is also studied by Mustafa Mamat et al. by using Matlab® and MultiSIM® softwares (Mustafa Mamat and Maulana 2013) .The difference between the two studies is that - the first one is the experimental study whereas the second one is a simulation study.

The secure communication systems with bi-directionally synchronized chaotic systems are also studied and constructed by many researchers over the time.Shuh-Chuan Tsay et al. are proposed and tested the feasibility of constructing the secure communication systems with the bi-directionally synchronized Lorentz and Chua's circuits (Shuh-Chuan Tsay and Chen 2004; Shuh-Chuan Tsay and Wu 2005) .A hardware demonstrator for chaotic cryptography and secure communications is also constructed by Emiliia Nazarenko et al. by using the synchronized Chua's circuits in a bi-directional line coupling (Emiliia Nazarenko and Katzenbeisser 2023)

So, now the two bi-directionally synchronized directly coupled identical Chua's circuits with a different coupling element called LC parallel circuit are proposed to construct a flexible and secure communication system.

In the present study, a secure communication system based on the chaotic masking method is proposed. The circuit construction, masking and recovery of the message signals are performed by using the LTspice software(LinearTechnology 2020, 2011) . A communication system is designed with the two bi-directionally synchronized identical Chua's circuits in direct LC parallel coupling. The values of the parameters L and C are chosen such that the complete synchronization is possible. Then, the message signal masking and recovery- the two key parameters of the efficient secure communication system are studied. The proposed system is proved to be flexible in construction and efficient in both signal masking and recovery when compared to the previously constructed secure communication systems.

METHODOLOGY

Mathematical Model of Coupled Chua's Circuits

Consider two Chua's circuits each one as shown in Fig.1. Let C_1, C_2 are the two capacitors, R is the linear resistor and L_1 is the inductor of the first Chua's circuit. Similarly, let C_3, C_4 are the two capacitors, $R^{'}$ is the linear resistor and L_2 is the inductor of second Chua's circuit. Suppose that these two Chua's circuits are coupled with a parallel combination of inductor L_3 and capacitor C_5 between the two positive ends of the capacitor C_1 of the first Chua's circuit and capacitor C_3 of the second Chua's circuit respectively. Non-linear resistor N_R of each Chua's circuit consists of two op-amps TL082 and six resistors in Kennedy's implementation.

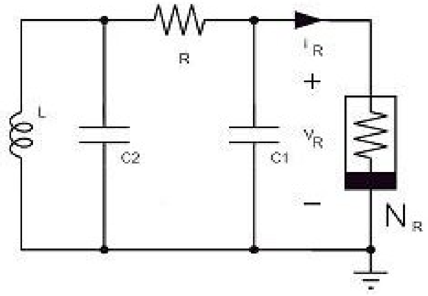

Figure 1 Basic schematic diagram of Chua's Circuit

The theory of coupled Chua's circuits can be obtained by applying the Kirchhoff's laws at the two ends of the resistance R and $R^{'}$ of the two Chua's circuits in the coupling:

Applying Kirchhoff's current laws at the two ends of the resistor R:

$$C_2\left(\frac{dV_{C_2}}{\mathrm{dt}}\right) = I_{L_1} + \left(\frac{V_{C_1} - V_{C_2}}{R}\right) \tag{1}$$

where V_{C_1} is the voltage across the capacitor C_1
V_{C_2} is the voltage across the capacitor C_2
and I_{L_1} is the current passing through the inductor L_1
Similarly:

$$\left(\frac{V_{C_2} - V_{C_1}}{R}\right) = C_1\left(\frac{dV_{C_1}}{dt}\right) + f(V_{C_1}) - (I_{L_3} - I_{C_5}) \tag{2}$$

where f (V_{C_1}) is a function giving the characteristics of Chua's diode

$I_{L_3}$is the current passing through the coupling inductor L_3
and $I_{C_5}$is the current passing through the coupling capacitor C_5
Here the piecewise-linear function f (V_{C_1}) of the Chua's diode is given by:

$$f(V_{C_1}) = G_b V_{C_1} + 0.5(G_a - G_b)(|V_{C_1} + E| - |V_{C_1} - E|) \tag{3}$$

where G_a and G_b are the conductance values and E is the breaking point of the voltage

Since the voltage developed between the two ends of the capacitor with capacitance C_2 is equal to the voltage across the inductor L_1 :

$$-L_1\frac{dI_{L_1}}{dt} = V_{C_2} \tag{4}$$

where $I_{L_1}$is the current passing through the inductor L_1

Similarly:

$$-L_3\frac{dI_{L_3}}{dt} = V_{C_3} - V_{C_1} \tag{5}$$

where $I_{L_3}$is the current passing through the inductor L_3 and V_{C_3} is the voltage across the capacitor C_3

Applying the scale transformation of the variables, the dynamical equations in the dimensionless form are given by:

$$\dot{x} = \alpha[y - x - f(x) + \rho - \epsilon] \tag{6}$$

(or) using Eq.(5):

$$\dot{x} = \alpha[y - x - f(x) + \gamma(1-\delta)\int (x' - x)d\tau] \tag{7}$$

$$\dot{y} = x - y + z \tag{8}$$

$$\dot{z} = -\beta y \tag{9}$$

where

$$\alpha = \frac{C_2}{C_1}, \beta = \frac{C_2R^2}{L_1}, \gamma = \frac{C_2R^2}{L_3} and \delta = \frac{I_{C_5}}{I_{L_3}} \tag{10}$$

$x = V_{C_1}/E$, $y = V_{C_2}/E$, $z = I_{L_1}R/E$
$\tau = t/R\,C_2$, $\rho = (I_{L_3}R/E)$, $\epsilon = (I_{C_5}R/E)$
and $\dot{x} = \left(\frac{dx}{d\tau}\right)$ etc.

Similarly, another set of equations are given by:

$$\dot{x'} = \alpha'[y' - x' - f(x') - \rho' + \epsilon'] \tag{11}$$

(or)

$$\dot{x'} = \alpha'[y' - x' - f(x') - \gamma'(1-\delta')\int (x' - x)d\tau'] \tag{12}$$

$$\dot{y'} = x' - y' + z' \tag{13}$$

$$\dot{z'} = -\beta' y' \tag{14}$$

where

$$\alpha' = \frac{C_4}{C_3}, \beta' = \frac{C_4R'^2}{L_2}, \gamma' = \frac{C_4R'^2}{L_3} and \delta' = \frac{I_{C_5}}{I_{L_3}} \tag{15}$$

$x' = \frac{V_{C_3}}{E}$, $y' = \frac{V_{C_4}}{E}$ and $z' = \frac{R' I_{L_2}}{E}$
$\tau' = t/R'C_4$, $\rho' = (R' I_{L_3}/E)$ and $\epsilon' = (R' I_{c_5}/E)$
and $\dot{x}' = \left(dx'/d\tau'\right)$ etc.

For two identical Chua's circuits:

$\alpha = \alpha'$, $\beta = \beta'$ and $\gamma = \gamma'$.

The difference equations are given by the differences p (τ), q (τ) and r (τ) defined by:

p (τ) = x (τ) - x' (τ)
q (τ) = y (τ) - y' (τ)
r (τ) = z (τ) - z' (τ)

From Eqs.(7), (8), (9) and Eqs.(12), (13), (14), the difference equations are given by:

$$\dot{p} = \alpha q - \alpha p - \alpha[f(x) - f(x')] - 2[\gamma(1-\delta)]\int p d\tau \tag{16}$$

$$\dot{q} = p - q + r \tag{17}$$

$$\dot{r} = -\beta q \tag{18}$$

From the Eq. (16), it is clear that for $\delta = 1$, the difference equations decouple from each other.

Since, the non-linear part is given by: f(x) - f(x') = $f'(\eta)$(x-x') ; a<$f'(\eta)$< 0, the equations assume the linear form:

$\dot{\xi}$ = A ξ

$$\text{where}\dot{\xi} = \begin{pmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{pmatrix}, \xi = \begin{pmatrix} p \\ q \\ r \end{pmatrix} \text{ and}$$

$$A = \begin{pmatrix} -\alpha - f'(\eta)\alpha & \alpha & 0 \\ 1 & -1 & 1 \\ 0 & -\beta & 0 \end{pmatrix} \tag{19}$$

When real parts of eigen values of the matrix A given by Eq.(19) are all negative, then the solutions of the system are stable. This is possible only when $f'(\eta)\alpha > 0$. This makes the synchronization globally stable(Liao Xiao-Xin LUE Hai-Geng and XUBing-Ji 2005).

Scheme of Secure Communication System

There are four essential components in the secure communication system based on the two LC parallel coupled identical Chua's circuits, as shown in Fig.2.In this system, the masked signal s(t) which is transmitted from the transmitter is the sum of chaotic signal x(t) and the message signal m(t).When the two identical Chua's circuits are completely synchronized through LC parallel circuit, the chaotic signal produced at the receiver is identical to the chaotic signal produced at the transmitter. Then, this chaotic signal x(t) is subtracted from the masked signal s(t) by the using the difference amplifier at the receiver and the message signal m(t) is extracted.

Transmitter: Transmitter is mainly a Chua's circuit. It is used for producing the chaotic signal.

Summing amplifier: Summing amplifier is an integral part of the transmitter. It is used to mix the message signal with the chaotic signal produced by the transmitter.

Receiver: Receiver is mainly another Chua's circuit and it is used to produce an identical chaotic signal through the process of synchronization.

Difference amplifier: This circuit is an integral part of the receiver and it is used to subtract chaotic signal from the masked signal.

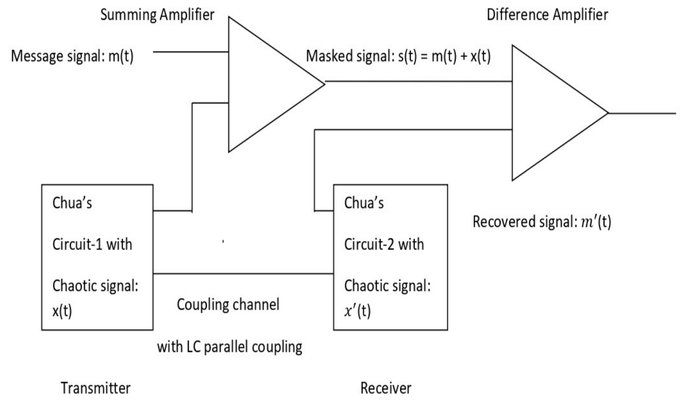

Figure 2 Schematic diagram of the secure communication system with two identical Chua's circuits in LC parallel coupling(at complete synchronization: $x'(t) = x(t)$ and $m'(t) = m(t)$)

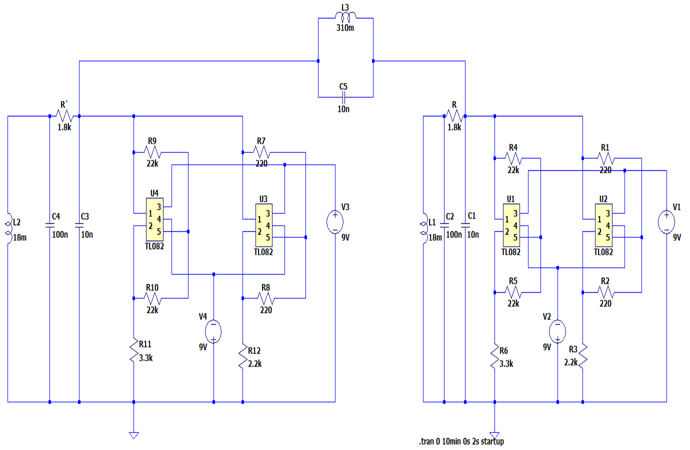

Figure 3 Chua's circuits in LC parallel coupling implemented with LT spice software for coupling parameters L_3 = 310 mH and C_5=10 nF.

Implementation in LTspice

LTspice is the Linear Technology's Simulation Programme with Integrated Circuit Emphasis. The basic version of this software was first developed at California University in the year 1972. The important feature of this software is that it is inexpensive and also consists of very extensive set of electronic component models. Apart from this, it facilitates the incorporation of some third party electronic device models like TL082 op-amp etc.

The two identical Chua's circuits in LC parallel coupling are constructed by using LTspice software, as shown in Fig.3. The components suggested in the Kennedy's paper are used, as shown in Table1(Kennedy 1992) . The synchronization is achieved by running the simulations for different values of the coupling inductance and coupling capacitance. The particular values for which the complete synchronization is observed to occur are used to construct the LC parallel coupled identical Chua's circuits to be used in constructing the secure communication systems.

The other supplementary sections of the communication system called summing amplifier and difference amplifier are also constructed by using the same LTspice software. Then, the secure communication system based on the two Chua's circuits in synchronization through LC parallel coupling is constructed, as shown Fig.4. The coupling used between two identical Chua's circuits is bi-directional as one Chua's circuit influences the other circuit and vice versa.

RESULTS AND DISCUSSION

Synchronization in LC parallel Coupling

Two Chua's circuits in LC parallel coupling are constructed with the components shown in Table1. Varying the inductance value L_3 for a fixed value of coupling capacitance of C_5=10 nF, the complete synchronization of the outputs of uncoupled capacitors in each Chua circuit is observed at the inductance values of L_3= 62 mH and 310 mH. This appears in Fig.5 and Fig.8 for the first and second cases respectively.

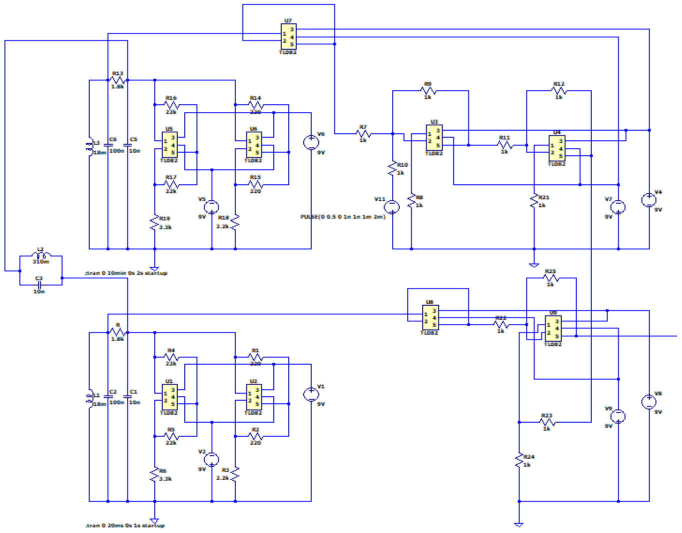

Figure 4 Chua's circuit based secure communication system implemented with LTspice software for coupling parameters L_2 = 310 mH and C_3= 10 nF

The synchronization errors up to 150 mV and 9 mV are observed in the first and second cases as shown in Fig.6 and Fig.9 respectively. The Lissajous figures confirming the complete synchronization in the first and second cases are given by the straight lines as shown in Fig.7 and Fig.10 respectively. Similarly, the complete synchronization of Chua's circuits is also observed at the coupling capacitance values of C_5= 2nF and 28nF at a fixed coupling inductance of L_3= 100mH. This can be seen in the first and second cases as shown in Fig.11 and Fig.14 respectively.

The synchronization errors up to 2 mV and 6 mV are observed in the first and second cases as shown in Fig.12 and Fig.15 respectively. The complete synchronization in the first and second cases is confirmed by the straight lines shown in Lissajous figures of Fig.13 and Fig.16 respectively. So, with these four sets of coupling inductance L_3 and coupling capacitance C_5values, the synchronized Chua's circuits in LC parallel coupling can be constructed for the use in the secure communication systems.

Table 1 Components in Chua's circuit in Kennedy's implementation

Sl. No	Component	Symbol	Value	Tolerance
1	Capacitor	C_1	10 nF	5%
2	Capacitor	C_2	100 nF	5%
3	Inductor	L_1	18 mH	5%
4	Resistance	R_1	220 Ω	5%
5	Resistance	R_2	220 Ω	5%
6	Resistance	R_3	2.2 kΩ	5%
7	Resistance	R_4	22 kΩ	5%
8	Resistance	R_5	22 kΩ	5%
9	Resistance	R_6	3.3 kΩ	5%
10	Battery	V_1	9 V	-
11	Battery	V_2	9 V	-
12	Op-amp(TL082)	A1	-	-
13	Op-amp(TL082)	A2	-	-
14	Potentiometer	R	2.0 kΩ	-

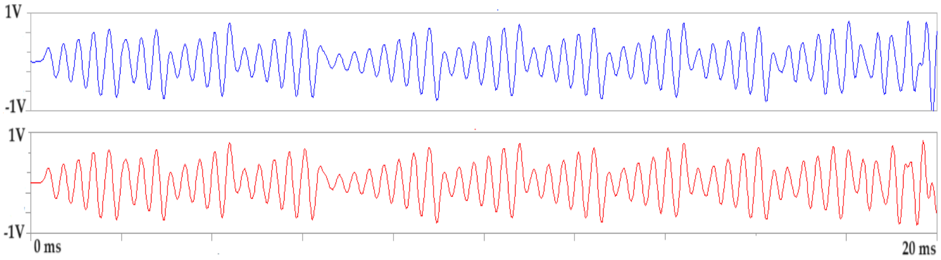

Figure 5 Time series graph of voltages across the capacitors C_2 and C_4 showing the synchronization at L_3 = 62 mH

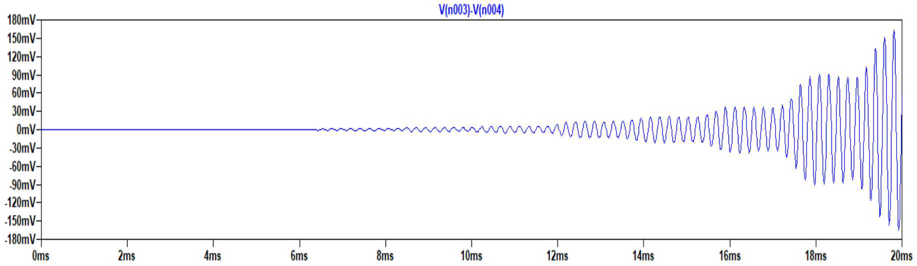

Figure 6 Error - time graph showing the synchronization error at L_3 = 62 mH

Secure Communication System with LC Parallel Coupling

A secure communication system is constructed with the synchronized Chua's circuits in LC parallel coupling with L_2= 62 mH and 310 mH with a fixed value capacitance C_3= 10 nF. A rectangular wave with amplitude of 0.5 V is used as the message signal. This message signal is recovered at the receiver in these two cases. The input and recovered message signals in the first and second cases are shown in Fig.17 and Fig.20 respectively.

The recovery of the message signal in the first and second cases is confirmed by the Lissajous figures shown in Fig.18 and Fig.21 respectively. This is because of the synchronization of chaotic signals at transmitter and receiver circuits due to LC parallel coupling. The

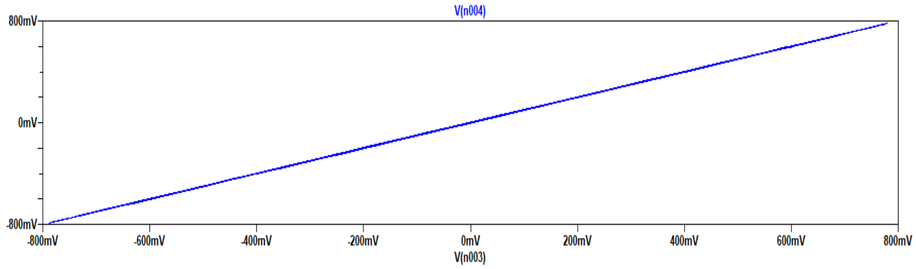

Figure 7 Lissajous figure of two chaotic signals **at** L_3 = 62 mH (X-axis: V_{c_4} and Y-axis: V_{C_2})

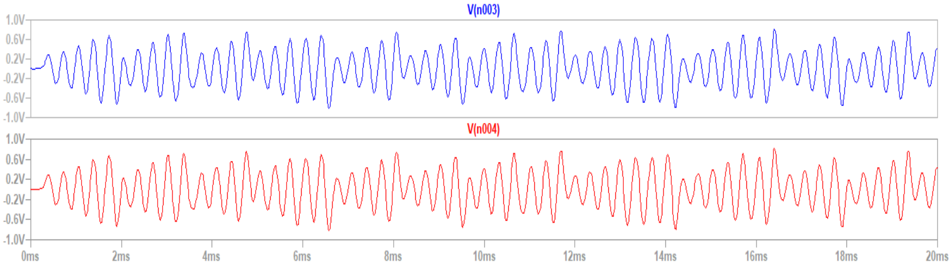

Figure 8 Time series graph of voltages across the capacitors C_2 and C_4 showing the synchronization at L_3 = 310 mH

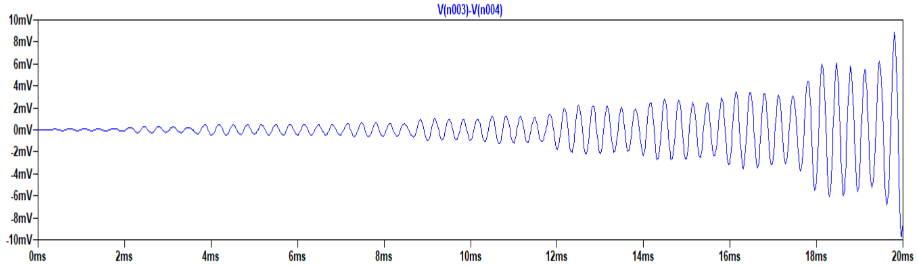

Figure 9 Error - time graph showing the synchronization error atL_3 = 310 mH (Error on Y- axis and time on X-axis)

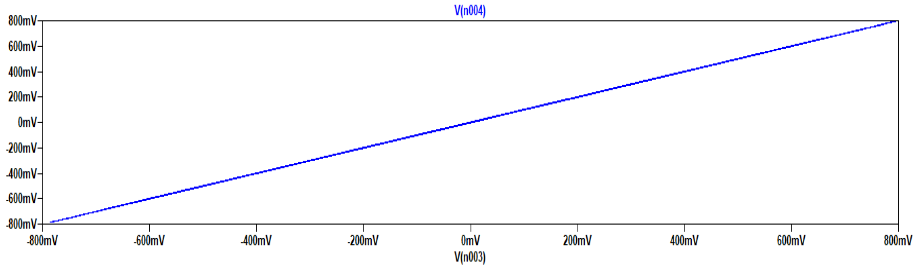

Figure 10 Lissajous figure of two chaotic signals at L_3 = 310 mH (X-axis: V_{c_4} and Y-axis: V_{C_2})

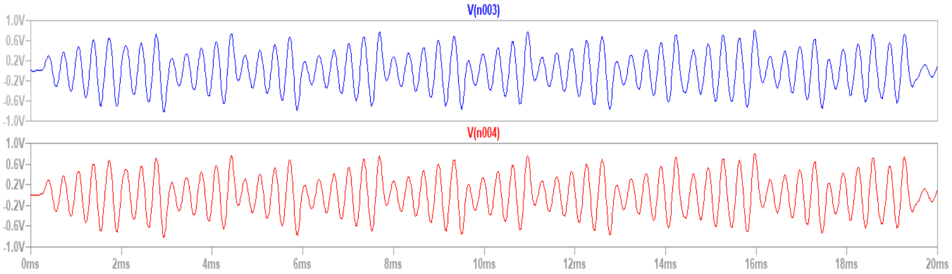

Figure 11 Time series graph of voltages across the capacitors C_2 and C_4 showing the synchronization at C_5 = 2 nF

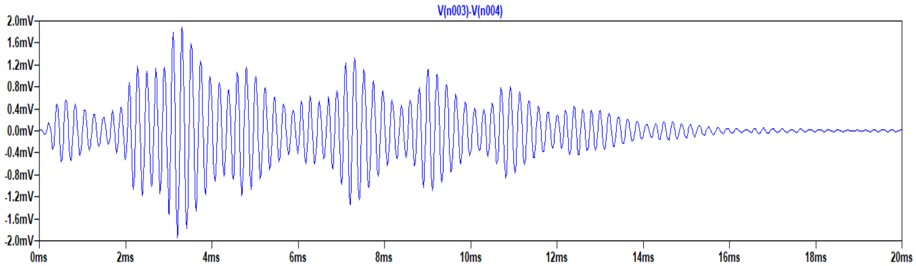

Figure 12 Error - time graph showing the synchronization error at C_5 = 2 nF (Error on Y- axis and time on X-axis)

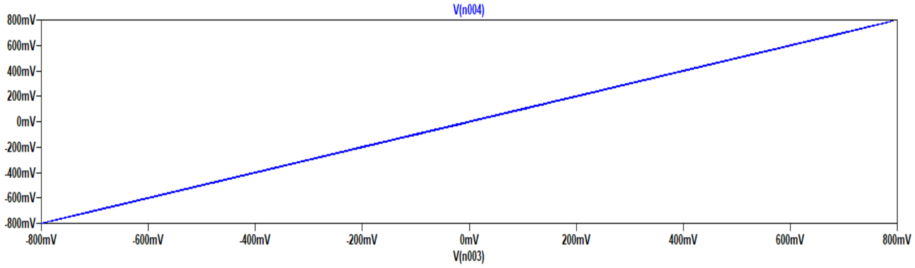

Figure 13 Lissajous figure of two chaotic signals **at**C_5 = 2 nF (X-axis: V_{c_4} and Y-axis: V_{C_2})

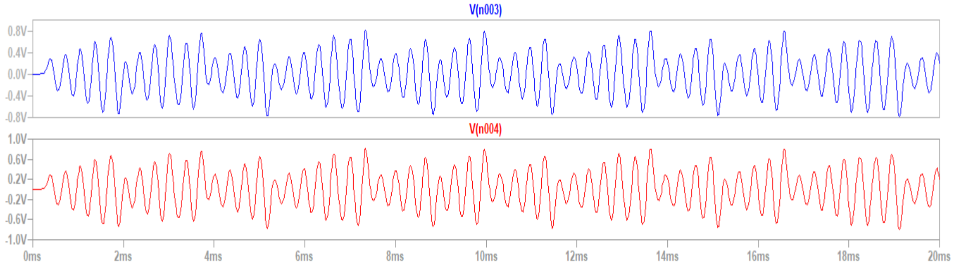

Figure 14 Time series graph of voltages across the capacitors C_2 and C_4 showing the synchronization at C_5 = 28 nF

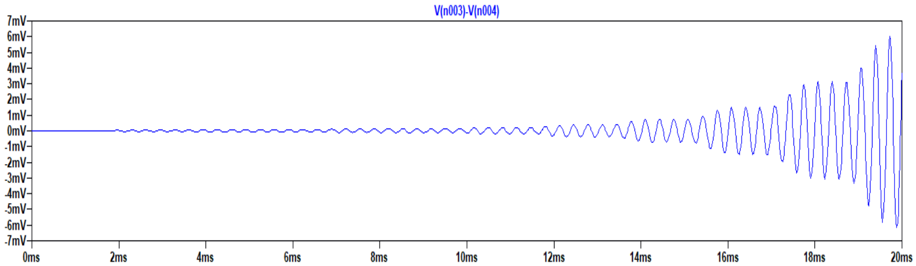

Figure 15 Error - time graph showing the synchronization error atC_5 = 28 nF (Error on Y- axis and time on X-axis)

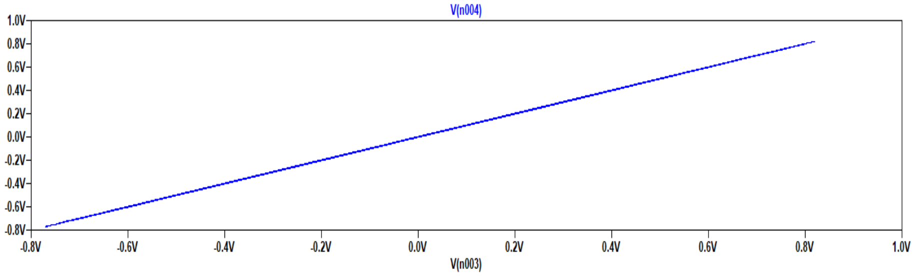

Figure 16 Lissajous figure of two chaotic signals at C_5 = 28 nF (X-axis: V_{c_4} and Y-axis: V_{C_2})

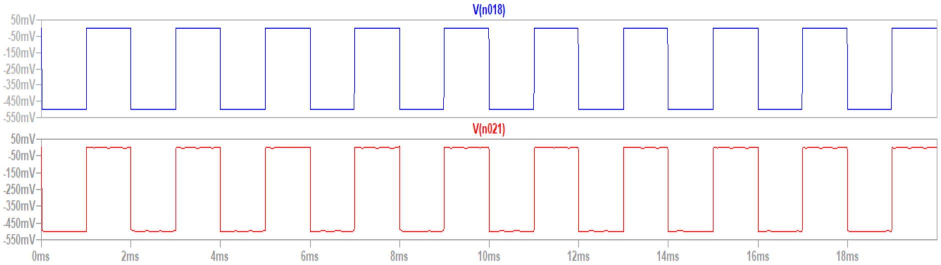

Figure 17 Time series graph of the input message and recovered signal at $L_2 \ = 62 \ mH$ and C_3= 10 nF

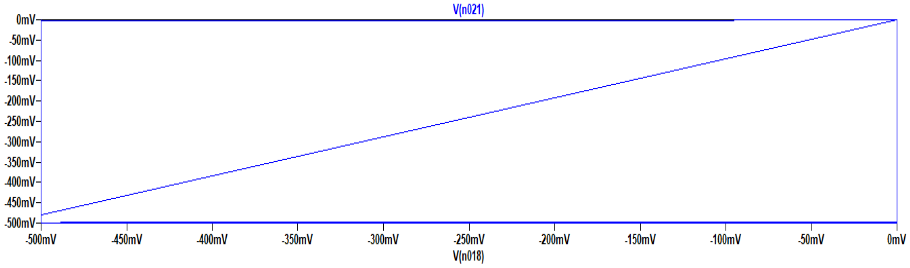

Figure 18 Lissajous figure of input and recovered message signals for $L_2 \ = 62 \ mH$ and C_3= 10 nF.

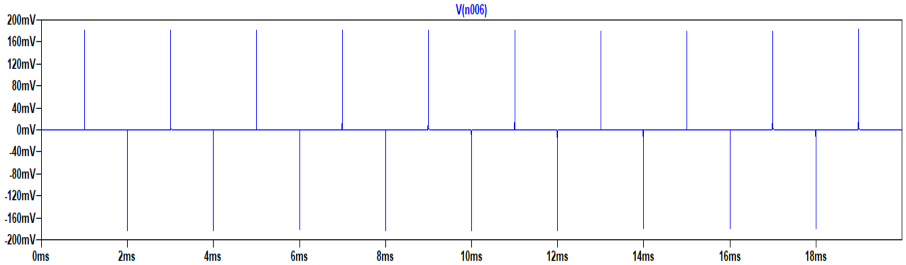

Figure 19 Masked signal at the transmitter for $L_2 \ = 62 \ mH$ and C_3= 10 nF

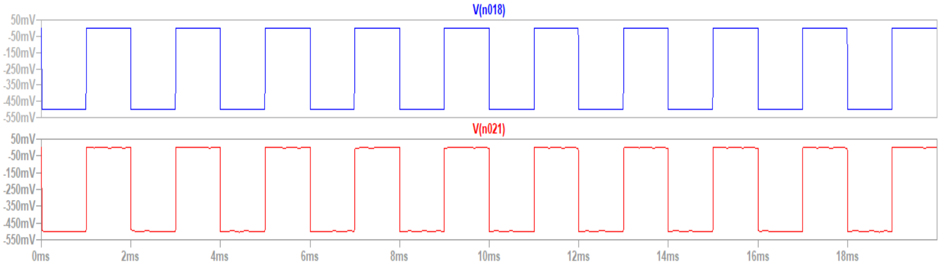

Figure 20 Time series graph of input and recovered message signals for $L_2 \ = 310 \ mH$ and C_3= 10 nF.

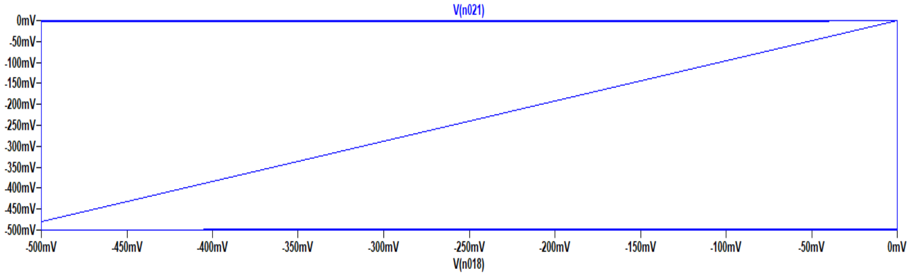

Figure 21 Lissajous figure of input and recovered message signals for $L_2 \ = 310 \ mH$ and C_3= 10 nF.

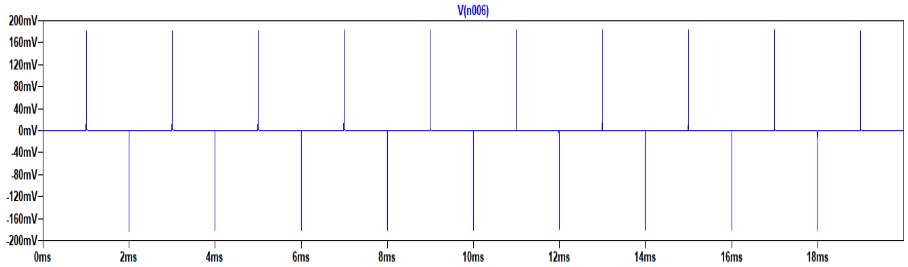

Figure 22 Masked message signal at the transmitter for $L_2 = 310\ mH$ and C_3= 10 nF

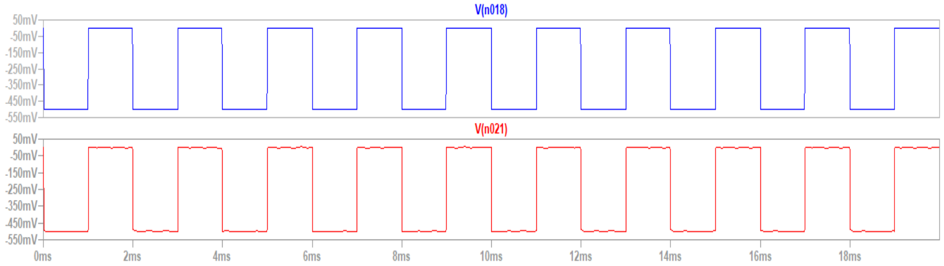

Figure 23 Time series graph of input and recovered message signals for $L_2 = 100\ mH$ and C_3= 2 nF

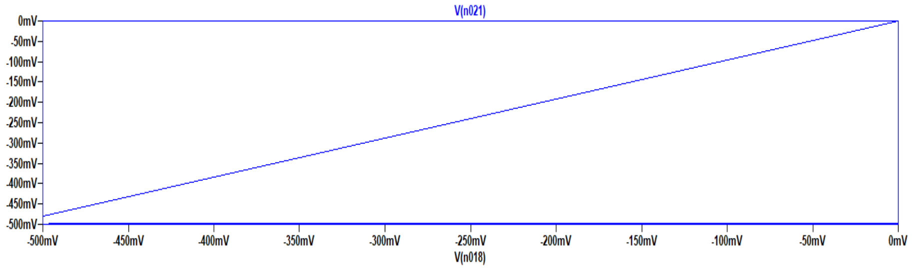

Figure 24 Lissajous figure of input and recovered message signals for $L_2 = 100\ mH$ and C_3= 2 nF.

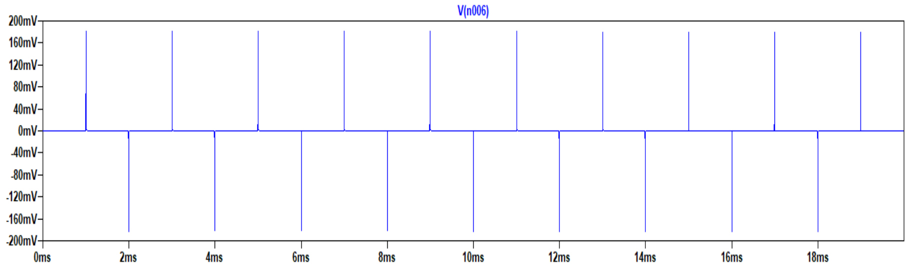

Figure 25 Masked message signal at the transmitter for $L_2 = 100\ mH$ and C_3= 2 nF.

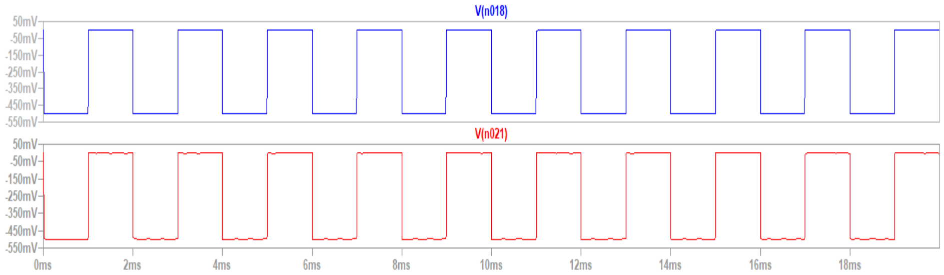

Figure 26 Time series graph of input and recovered message signals for $L_2 = 100\ mH$ and C_3= 28 nF.

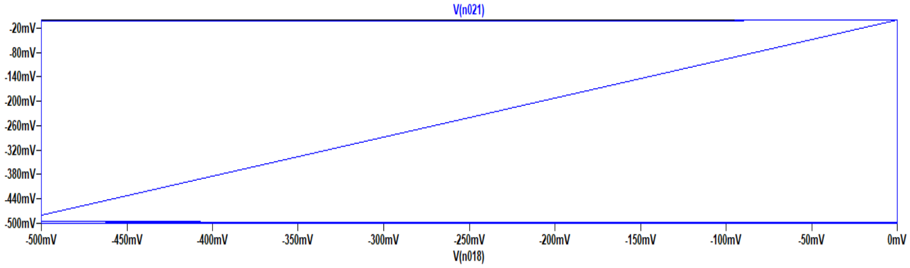

Figure 27 Lissajous figure of input and recovered message signals for $L_2 = 100\ mH$ and C_3= 28 nF.

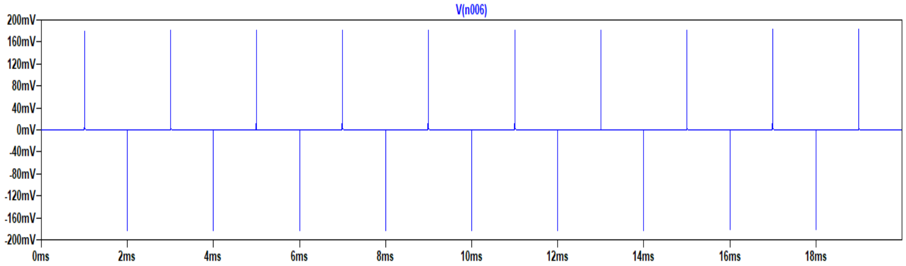

Figure 28 Masked message signal at transmitter for $L_2 = 100\ mH$ and C_3= 28 nF.

recovered signals are identical to those of input rectangular waves except small fluctuations about the horizontal portions. This is the result of small synchronization error in the respective cases. The masked signals in the first and second cases are shown in Fig.19 and Fig.22 respectively. The masked signals are concealing the identity of the original message signal, so that the actual message signal cannot be identified, except after the recovery at the receiver.

Similarly, a secure communication systems is constructed with the coupling capacitance values of C_3= 2 nF and 28 nF for a fixed coupling inductance value of L_2 = 100 mH. The message signals are recovered in this case also for the same input signal as before as the complete synchronization is achieved in this case as well. The input and recovered signals in first and second cases are shown in Fig.23 and Fig.26 respectively. The complete synchronization is confirmed in first and second cases by the Lissajous figures shown in Fig.24 and Fig.27 respectively. The input rectangular waves are completely recovered here except for very few small deviations just below and above the horizontal portions. The reason for this is again a small synchronization error in the respective cases. The masked signals in the first and second cases are shown in Fig.25 and Fig.28 respectively.

The message delivery is secure in this case also as the message signals are completely masked by the input chaotic signals.So, the proposed secure communication system constructed with synchronized Chua's circuits in LC parallel coupling can be used for efficient signal masking and delivery at all the four sets of coupling inductance and capacitance values. So, there is the greater flexibility in the construction and the efficiency in the working of the proposed communication system compared to the previous studies (Mustafa Mamat and Maulana 2013; Emiliia Nazarenko and Katzenbeisser 2023).

CONCLUSION

A new secure communication system is constructed by using the chaotic masking method. For this purpose, two identical synchronized Chua's circuits in a new LC parallel coupling are used. The advantage of this LC parallel coupling is that the complete synchronization can be achieved for various sets of coupling inductance and capacitance values.This provides some flexibility in constructing the secure communication systems with perfect masking and recovery of the message signals as observed through the time series graphs and Lissajous figures generated in LTspice simulations. These results are also good compared to the previous studies of using the same bi-directional coupling of two Chua's circuits but with some different coupling elements. So, the efficient secure communication systems can be practically constructed by using the synchronized Chua's circuits in the direct LC parallel coupling.

Furthermore, the bi-directional nature of coupling used here also provides some additional security in the message transmission, even if the coupling elements of the system are known to the intruder. A few limitations of such LC coupled based communication systems are mainly - the complexity in the construction due to the complexity in constructing the coupling element and the mathematical analysis of the problem.

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.

Ethical standard

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

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