Spread Spectrum Communication System with Particle in a Box Electronic Circuit

José Carlos Pizolato, Jr. and Luiz Gonçalves Neto

Abstract—A spread spectrum communication system based on the electronic model of the particle in a box system is proposed. This circuit allows a robust and simple electronic emulation of the mechanical behavior of the collisions of a particle inside a box, exhibiting rich chaotic behavior. The required nonlinearity to emulate the box walls is implemented in a simple way when compared with other analog electronic chaotic circuits. In this system, binary data stream information is transformed in the frequency modulated signal by the binary frequency shift keying (BFSK) modulator. The chaotic signal of the particle in a box electronic circuit is used to generate a broadband signal in the voltage controlled oscillator (VCO) of the transmitter. The frequency hopping signal send to receiver is generated by mixing the binary frequency shift keying and the broadband signal. The demodulation process is done when the VCOs of transmitter and receiver are synchronized by a phase lock loop (PLL) circuit. The performance of the proposed system is verified through the eye pattern technique applied on the binary bit stream. A binary data stream information was recovered by a frequency shift keying (FSK) demodulator that uses the resulting signal generated by the product between the VCO and the received signal. The experimental results demonstrated that the particle in a box electronic circuit can be used in a spread spectrum communication system.

Index Terms—Spread Spectrum, Frequency Hopping, Chaotic Circuit, Particle in a Box Electronic Circuit.

I. INTRODUCTION

In conventional spread spectrum communication systems pseudorandom signals are used for broadening the spectrum by modulating the phase (in direct-sequence), or the frequency (in frequency hopping (FH)) of the carrier signal, which provides a better antijam performance, low power spectral density, and implies the reduction of multipath effects [1]. At the receiver a corresponding despreading technique is used to reconstruct the baseband signal. Despreading techniques usually require synchronization between the transmitter and the receiver.

There has been significant interest in exploiting chaotic dynamics in communications [2-8]. Chaotic systems provide a rich mechanism for pseudo-random signal generation, with potential applications to spread spectrum communication systems [4,9-13]. Analog chaotic oscillators provide a natural way of generating smoothly varying frequency modulation (FM) [14]. In the literature there are several electronic circuits which can be used to generate chaotic signals for applications in frequency modulation. Some examples are the Chua’s circuit [4, 15, 16], the Lorenz-based chaotic circuit [9], the chaotic Rössler circuits [17] and the particle in a box electronic circuit [18].

Usually chaos synchronization is very susceptible to channel noise, distortions, and interference. To minimize the performance degradation associated with these factors, communication systems based on chaotic pulse position modulation and chaotic frequency modulation (CFM) have recently attracted much interest [1,14]. The CFM communication scheme is a modification of the frequency hopping scheme, in which a chaotic signal is used to spread the spectrum instead of a pseudo-noise sequence. A spread spectrum communication system which uses CFM for spreading the spectrum and BFSK modulation for the information signal was proposed in reference [1]. In that work the Rössler system was used as the chaotic oscillator. However, the analog implementation of the chaotic circuit requires several operational amplifiers and components. Reference [18] presents the particle in a box electronic circuit. In that article the nonlinearity is implemented in a simple way and with fewer analog devices when compared with other analog electronic chaotic circuits.

This paper proposes the application of the particle in a box electronic circuit to implement a communication system which uses the CFM for spreading the spectrum and BFSK to modulate the information signal. In the electronic implementation of this system, the transmitter has the particle in a box electronic circuit which controls the voltage control oscillator (VCO) to generate a broadband signal. On the receiver there is a phase lock loop (PLL) circuit to do the synchronism between the VCOs of the transmitter and receiver. The binary data stream is recovered by a frequency shift keying (FSK) demodulator that uses the resulting signal generated by the product between the VCO and the received signal. The performance of the proposed system is verified through the eye pattern technique [19] applied on the binary
data stream recovered at the receiver. In the demodulation process, the robustness of the spread spectrum system was evaluated with the box electronic circuit. The transmission channel was simulated using the model “T” transmission line. The eye patterns were constructed for transmission lines with 1000 meters and 5000 meters.

This paper is organized as follows. In section II, it is discussed the electronic circuit implementation of the particle in the box electronic circuit system. This circuit will be used in the implementation of the analog chaotic oscillator. In section III, the particle in the box electronic circuit is applied in an alternative spread spectrum frequency hopping system. In section IV, the performance of the alternative frequency hopping system is evaluated through the eye pattern technique. Any conclusions about the experimental tests are done in the section V.

II. THE ANALOGIC CHAOTIC OSCILLATOR

The particle in a box electronic circuit described in Fig. 1 was used in a secure communication system [18]. This circuit simulates the mechanical behavior of the collisions of a particle inside a box. It is based on the "electronic bouncing ball circuit", proposed by Zimmerman, Selasch and Neto [20], which is used to study the regular, chaotic and random behavior of a bouncing ball on a vibrating surface. The key devices of the particle in a box electronic circuit are the anti-parallel diodes \((D_1 \text{ and } D_2)\) in series with the resistor \(R_L\) of the particle in a box electronic circuit. This circuit simulates the mechanical behavior of the collisions of a particle in walls in the \(x\) direction, resulting in the term \(I_D(V_2)\) shown in Fig. 2.

![Fig. 1: The particle in a box electronic circuit described by equation (1). The component values are: resistors (kΩ): \(R_1=47\); \(R_2=R_3=R_5=10\); \(R_L=0.51\); capacitors (nF): \(C_1=C_2=12\); diodes \(D_1\) \& \(D_2\): 2N4148; Operational Amplifiers: 741 or equivalents. This circuit simulates the mechanical behavior of the collisions of a particle inside a box.](image1)

\[
I_D(V_2) = \frac{1}{R_2} \frac{dV_2}{dt} + \frac{1}{R_1} \frac{dV_1}{dt} + I_D(V_2) = -\frac{V_E}{R_E} \tag{1}
\]

In the equation (1), the signal \(V_2\) corresponds to the position \(x\) of the system described in Fig. 1, and the signal \(dV_2/\,dt\) corresponds to the velocity \(dx/\,dt\). The component values are: Resistor (kΩ): \(R_1 = 47\); \(R = R_E = R_2 = 10\); \(R_L = 0.51\); capacitors (nF): \(C_1 = C_2 = 12\); diodes \(D_1\) \& \(D_2\): 2N4148; Operational Amplifiers: CI 741 or equivalents. The components of the operational amplifiers can be seen in the reference [21]. All resistors and capacitors used in this work have an error of +/- 10% in their nominal values.

The periodic or chaotic behavior can be obtained by the variation of the parameter of bifurcation of the circuit in Fig. 1, which controls the dynamic of the system. The variation of the parameters \(w\) or \(V_{\max}\) of the input sinusoidal signal \(V_E = V_{\max} \sin(\omega t)\) can be used as the bifurcation parameters. As a first example to show the dynamic of the chaotic behavior of the particle in a box system, the amplitude \(V_{\max}\) has been chosen as parameter of bifurcation. The initial conditions of this circuit were \((V_2 = 0 \text{ and } dV_2/\,dt = 0)\). The variation of \(V_{\max}\) can causes a periodic oscillation with period \(T\), passing by a period doubling bifurcation, respectively with period \(2T\) and \(4T\), until a non-periodic chaotic oscillation. In the electronic simulation of this system, the period doubling bifurcation is limited to \(4T\) due to the noisy level present in the circuit [20]. This period doubling behavior followed by the chaotic oscillations is shown in the phase diagrams of Fig. 3.
The particle in the box electronic circuit has been used in the communication system [18]. This circuit is implemented in a simple way and with fewer analog devices when compared with other analog electronic chaotic circuits. In this work it is proposed the application this circuit as the analog chaotic oscillator in an alternative spread spectrum frequency hopping (FH) system.

III. APPLICATION OF THE PARTICLE IN THE BOX ELECTRONIC CIRCUIT IN A SPREAD SPECTRUM SYSTEM

A conventional spread spectrum system by frequency hopping is illustrated in Fig. 4. A frequency generator generates a carrier with a random frequency using a pseudo random sequence. The recovery process of the information is obtained when the receiver synchronizes with the transmitter. The carrier signal has a frequency in each instant and it has a wideband in frequency domain. An alternative way to generate the carrier with random frequency applies an analog chaotic oscillator. The block-diagram of this system is shown in Fig. 5.

The spreading of information in the transmitter is done by the particle in the box electronic circuit of Fig. 1. The input sinusoidal signal $V_E = V_{\text{max}} \sin (w t)$ is chosen to get a phase diagram of Fig. 3(d) with $V_{\text{max}} = 2.93V$ and $w = 12208 \text{ rad/s}$ to the initial conditions $(V_2 = 0 \text{ and } dV_2 / dt = 0)$. The chaotic signal $V_2(t)$ in the output of the second operational amplifier of this circuit is

\[ \dot{\phi}_t = w_o (1 + m_t V_2) \]  

(2)
in which \( w_n \) is the ‘natural’ frequency of VCO, \( m_1 \) is the modulation gain coefficient (\( m_1 = 0.11 \)) and \( V_2(t) \) is the chaotic signal.

The input information \( d(t) \) (a binary data stream) is applied in the FSK modulator generating the BFSK signal \( S_r(t) \) of Fig. 7(a) with the power spectrum shown in Fig. 7(b).

The FSK modulator block was electronic implemented with CI ICL8038. The BFSK signal and the chaotic sinusoidal carrier are multiplied by the phase discriminator block (⊗) resulting in the spread spectrum signal of Fig. 8. The block (⊗) was electronic implemented with CI MM74C932. The signal \( V(t) \) of Fig. 8 has a wideband from 20 kHz to 60 kHz and it is described by equation (3).

\[
V(t) = P_s \cos(w_c t + \Omega dt + \theta)
\]

in which \( P_s \) is the amplitude of the signal \( S_r \), \( w_c \) is carrier frequency, \( d(t) \) is the binary data stream information, \( \Omega \) is a parameter of the FSK modulator and \( \theta \) is a phase factor.

The local VCO, the phase discriminator (⊗) and the low pass filter (LPF) form a phase locked loop (PLL). The LPF has the transfer function done by equation (4).

\[
K(s) = \frac{1}{1 + T_f s}
\]

in which \( T_f \) is the time constant of the filter.

The frequency detection is performed using the PLL that synchronizes transmitter and receiver. In this case the frequency of VCO is described by equation (5).

\[
\phi_r = w_c(1 + m_2 u(t))
\]

in which \( m_2 \) is the modulation gain coefficient (\( m_2 = 0.12 \)) and \( u(t) \) is the output signal of the LPF.

If the PLL is able to compensate the frequency deviations and keep the VCOs synchronized, the sinusoidal carrier with chaotic variable frequency \( w_c \approx w_i \) can be recovered in the receiver. After, the BFSK signal \( S_r(t) \) is recovered using the phase discriminator block (⊗) and a FSK demodulator is used to recovery the binary data stream \( \hat{d}(t) \) from \( S_r(t) \) signal.

The block FSK demodulator was electronic implemented with CI LM565.

Fig. 6. Chaotic signal \( V_2 \) of the particle in the box electronic circuit with the initial conditions \( (V_2 = 0 \) and \( dV_2/dt = 0 ) \).

The input information \( d(t) \) (a binary data stream) is applied in the FSK modulator generating the BFSK signal \( S_r(t) \) of Fig. 7(a) with the power spectrum shown in Fig. 7(b).

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If the PLL is able to compensate the frequency deviations and keep the VCOs synchronized, the sinusoidal carrier with chaotic variable frequency \( w_c \approx w_i \) can be recovered in the receiver. After, the BFSK signal \( S_r(t) \) is recovered using the phase discriminator block (⊗) and a FSK demodulator is used to recovery the binary data stream \( \hat{d}(t) \) from \( S_r(t) \) signal. The block FSK demodulator was electronic implemented with CI LM565.
The eye pattern technique [19] is used to verify the performance of the recovery process of the binary data stream. A recovery process without bit error should have a pattern like an opened eye. Fig. 9(a) illustrates the recovery process with transmission line like a short line circuit. The pattern is an opened eye because the communication process does not present high level of bit error. Fig. 9(b) illustrates other recovery process with transmission line of 1000 meters. In this figure the eye is closer than the last case because of the bit errors introduced by the length of the transmission line. Fig. 9(c) illustrates the recovery process with transmission line of 5000 meters. In this case, the eye pattern is closer than the case with transmission line of 1000 meters. The recovery process presents problems such as high amplitude distortion, temporization errors and phase distortion (timing jitter). These eyes pattern show the influence of the length of transmission line in the quality of detection.

V. CONCLUSION

A possible approach to spread spectrum communication system was demonstrated. In this paper it was implemented a spread spectrum communication system frequency hopping that uses an analog chaotic circuit. The particle in a box electronic circuit was used like the analog chaotic circuit. The rich chaotic behavior of this circuit was used in to generate a sinusoidal carrier with random variable frequency. This circuit was chosen because it is implemented in a simple way and with fewer analog devices when compared with other analog electronic chaotic circuits. The performance of the systems was verified through the eye pattern of the recovered binary data stream. The recovery process presented problems such as high amplitude distortion, temporization errors and phase distortion (timing jitter). The eyes pattern showed the influence of the length of transmission line in the quality of detection. The experimental results in this paper show that the particle in a box electronic circuit is an interesting alternative to implement a spread spectrum communication system.

REFERENCES


José Carlos Pizolato, Jr., received the B.Sc degree in electrical engineering from Escola de Engenharia de São Carlos (EESC), University of São Paulo, São Paulo, Brazil, in 1998, the M.Sc. degree in electrical engineering (chaotic modulation as an alternative to spread spectrum systems) from Escola de Engenharia de São Carlos, University of São Paulo, São Carlos, Brazil, in 2001, and the Ph.D. degree in electrical engineering from EESC in 2006. He is currently an Associate Professor with the University of São Paulo, São Carlos. He is the Topical Editor of the Journal of Applied Optics.