A Novel Chaos Based ASK–OOK Communication System

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***Abstract*–This paper proposes the novel broadband chaos and chirp based noncoherent amplitude shift keying (ASK) – on off keying (OOK) communication systems. Their theoretical probability of error expressions are derived and confirmed with the corresponding empirical bit error rate (BER) simulations demonstrating that they match the BER performance of the traditional narrowband system. The superiority of the newly proposed broadband systems over the traditional narrowband systems is then demonstrated in the presence of narrowband interference. This is a particularly important find as the traditional narrowband ASK–OOK systems are known to be highly susceptible to interference. Finally, it is demonstrated that the interference performance of the proposed chaos based system can be further improved by optimising chaos based signals for BER using the downhill simplex algorithm.**

Keywords-Chaos; communications; ASK-OOK; interference;

I. INTRODUCTION

In chaotic communication systems a message signal directly modulates a broadband chaotic signal [1]-[3]. However, it is also possible to indirectly utilise a chaotic signal [4][5] to modulate a sinusoidal signal and thus create a constant envelope chaos based signal [5]. The chaos based signal may then be further modulated by a binary message signal to form a broadband amplitude shift keying (ASK) – on off keying (OOK) communication system as proposed in this paper. The ASK–OOK communication systems find use in radio frequency identification (RFID) devices as well as in medical applications such as endoscopy [6], among other. However, the traditional narrowband sine based ASK–OOK systems [7], where bits 0 are represented by no signal and bits 1 by a sinusoidal carrier, are highly sensitive to interference [6]. Therefore, the motivation for the use of the broadband chaos and chirp based carrier signals in place of a narrowband sinusoidal carrier signal within the ASK–OOK systems stems from the fact that broadband signals are more resistant to interference than narrowband signals.

In Section II, a novel broadband chaos based ASK–OOK system is proposed and its theoretical probability of error expression derived and confirmed by the corresponding empirical BER. Section III proposes the novel broadband chirp based ASK–OOK system and demonstrates its matching BER performance to that of the chaos based system and the traditional narrowband system. In Section IV, it is demonstrated that that the novel chaos based ASK–OOK system offers increased resistance to the narrowband interference when compared to the traditional narrowband sine based carrier and the novel broadband chirp based carrier systems. Finally, Section IV also shows that the novel broadband chaos based system can be optimised to further improve its BER in the presence of narrowband interference.

II. CHAOS BASED ASK-OOK SYSTEM

The proposed broadband chaos based ASK–OOK communication system is shown in Fig. 1 where a binary signal m modulates a continuous chaos based signal. A systematic approach of generating continuous time signals by chaos generators was proposed in [4]. The concept was used in [5] to generate the sinusoidal chaos based signals for radar applications. A chaos based signal, similar to that of [5], is generated here for the application within the novel communication system by modulating the sinusoidal carrier of (1):

$$s(t) = A\sin\left[\frac{2\pi t}{7\xi(j)}\right] \quad \text{where:} \quad [t = 0, 1 \ldots t < 7\xi(j)] \tag{1}$$

by a chaotic signal $\xi(j)$. The chaos based signal, $s(t)$, is then modulated by a binary message signal, $m(t)$, as expressed by (2):

$$x(t) = m(t)\cdot s(t) \qquad \text{where:} \quad m(t) \in \{0, 1\} \tag{2}$$

Finally, the modulated signal of (2), $x(t)$, is transmitted over the additive white Gaussian noise (AWGN) channel, as illustrated in Fig. 1.

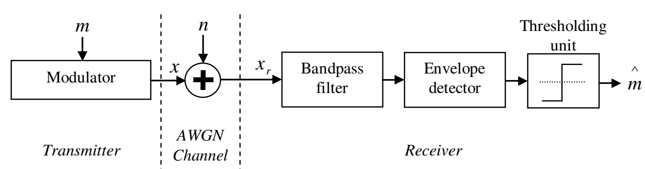

Figure 1. The noncoherent chaos based ASK-OOK wireless communication system in an AWGN channel.

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The bandpass filter of Fig. 1 filters out all but the frequencies surrounding the centre frequency of the received signal, x_r. Theoretically, the minimum bandwidth of the bandpass filter that can be implemented is equal to the bit rate $R_b = (1/T_b)$ Hertz, where T_b denotes the bit period. Accordingly, the bandwidth of the chaos based, that is, the transmitted signal, must be kept within the system bandwidth R_b.

The total fixed number of samples within the chaos based carrier signal was chosen to be 100, that is, 100 samples were chosen to represent any bit. The sample length of 100 was found to adequately represent a chaos based carrier signal of (1) and also yield a sufficiently low number of samples per bit what allowed for relatively fast Monte Carlo BER simulations. As it has not been established whether the signal $s(t)$ of (1) is chaotic, it is referred to as a chaos based rather than a chaotic signal [5]. The chaotic map $\xi(j)$ of (1), used to modulate (1), was proposed by Carroll in [5]:

$$\begin{aligned} y_{j+1}(1) &= \left[\sum_{i=2}^{N} p(i)\, y_j(i)\right] \bmod 1, \\ y_{j+1}(i) &= y_j(i+1) \qquad (i = 2,3 \ldots N-1), \\ y_{j+1}(N) &= y_j(1), \\ \xi(j) &= y_j(1) + 0.5 \qquad (j = 1,2 \ldots M), \end{aligned} \tag{3}$$

where $p(i)$ are the system parameters. The largest Lyapunov exponent of $\xi(j)$ was determined to be 0.097 bits/iteration [5] thus proving that the proposed system of (3) is chaotic. For a system to be chaotic, its largest Lyapunov exponent must be greater than 0 [8].

For every chaotic sample of (3), there is a certain higher number of chaos based signal samples of (1) [5]. The number of chaos based signal samples per chaotic value is higher for higher chaotic signal values and lower for lower values. The reason for this can be observed by examining (1) from which it can be seen that higher $\xi(j)$ chaotic values produce lower frequency components and more samples per each sinusoidal cycle of the chaos based signal. Opposite is true for lower $\xi(j)$ chaotic values which produce higher frequency components and less samples per sinusoidal cycle of the chaos based signal. Therefore, in contrast to a linear frequency modulated (LFM) chirp signal [9] whose frequency changes linearly, frequency components of a chaos based signal change in a chaotic fashion.

The empirical distributions of the decision variables of the newly proposed broadband chaos based ASK–OOK system of Fig. 1 are plotted in Fig. 2 at the bit energy to noise power spectral density (*Eb/No*) ratio of 10 dB, demonstrating the Rayleigh and Rician distribution of bits 0 and 1, respectively.

As the energy of a narrowband sinusoidal signal $(A^2T/2)$ [8][10] is independent of its frequency and only depends on its amplitude and signal duration, it can also be shown that the energy expression of the sinusoidal chaos based signal of (1) is governed by the same expression. To demonstrate this, (1) is first rewritten in the form of (4):

$$s(t) = \sin[2\pi\, \Delta f\; t] \tag{4}$$

where $\Delta f = 1/[7\,\xi(j)]$ denotes the changing frequency with chaotic values. The chaos based signal energy is then obtained by squaring and integrating (4) over the signal duration T:

$$\begin{aligned} E &= \int_0^T (A \sin[2\pi\, \Delta f\; t])^2\, dt \\ &= \frac{A^2}{2}\int_0^T dt - \frac{A^2}{2}\int_0^T (\cos[4\pi\, \Delta f\; t])\, dt \\ &= \frac{A^2 T}{2} \end{aligned} \tag{5}$$

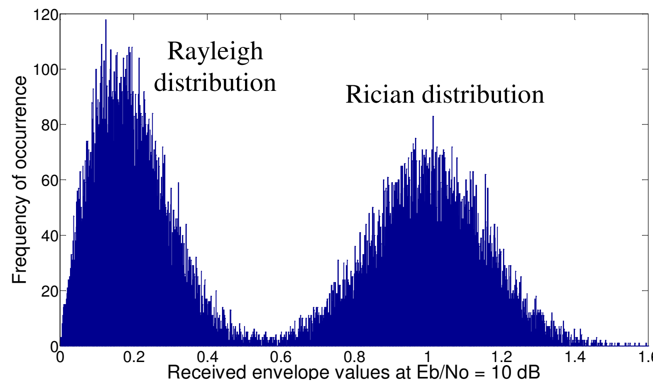

Figure 2. Histogram of the received envelope values at the *Eb/No* ratio of 10 dB for the novel chaos based ASK–OOK system.

By setting the signal duration T of (5) equal to the bit period T_b, bit 1 energy equal to $A^2T_b/2$ is obtained. Furthermore, as the bits 0 are represented by no signal their energy is zero, resulting in an average energy per bit of $E_b = A^2T_b/4$ [7]. Therefore, the chaos based signal energy is identical to that of a narrowband sinusoidal signal [7][10].

As the distribution of the decision variables and the energy of the chaos based signal match those of the traditional narrowband sine based ASK-OOK system [7] it is expected that the probability of error of the two systems will be identical. The probability of error (P_e) is obtained by considering the distribution of the decision variables sampled from the envelope at the input to the thresholding unit of Fig. 1. Accordingly, the probability of error that a bit 1 is received when a bit 0 was transmitted is obtained by integrating the Rayleigh probability density function representing bits 0 for the values when the decision threshold $\alpha = A/2$ is exceeded:

$$P_{e_0}(\alpha) = \int_\alpha^\infty \frac{r}{\sigma^2} e^{-r^2/(2\sigma^2)}\, dr = e^{-\alpha^2/(2\sigma^2)} \tag{6}$$

where σ^2 denotes the variance (power) of the AWGN at the input of the envelope detector, A the amplitude of the chaos based carrier and r the random variable. The noise power at the input to the envelope detector is bandwidth limited by the filter of bandwidth $B_p = R_b$ and is thus expressed as: $\sigma^2 = \frac{N_o}{2} 2B_p = N_o R_b$. Similarly, the probability that a bit 0 is received when a bit 1 was transmitted is obtained by integrating the Rician probability density function representing bits 1 for the values when the decision threshold α is not exceeded:

$$P_{e_1}(\alpha) = \int_0^{\alpha} \frac{r}{\sigma^2} e^{-(r^2+A^2)/(2\sigma^2)} I_o\left(\frac{rA}{\sigma^2}\right) dr = 1 - Q_M\left(\frac{A}{\sigma}, \frac{\alpha}{\sigma}\right) \qquad (7)$$

where I_o denotes the modified Bessel function of the first kind of zero order. The integral term of (7) was put into the form of the Marcum Q function [11]: $Q_M(a,\beta) = \int_{\beta}^{\infty} x\, e^{(-(x^2+a^2)/2)} I_o(ax)dx$ by making the definition: $x = r/\sigma$, so that $dx = dr/\sigma$ and substituting those into the integral term to obtain the final result of (7).

The probability of error for equiprobable bits 0 and 1 is then determined by finding the average value of (6) and (7), to obtain the exact P_e expression for the noncoherent chaos based ASK-OOK system:

$$P_e(\alpha) = \frac{1}{2}\left(e^{-\alpha^2/(2\sigma^2)} + 1 - Q_M\left(\frac{A}{\sigma}, \frac{\alpha}{\sigma}\right)\right) \qquad (8)$$

Equation (8) is plotted in Fig. 3a alongside the corresponding empirical BER curve obtained via the Monte Carlo simulation of the chaos based ASK–OOK system of Fig. 1. It can be observed that the two plots exhibit a perfect match and thus prove the result of (8). Furthermore, as expected, the result of (8) matches the result for the probability of error of the traditional narrowband ASK-OOK system whose theoretical probability of error expression was derived in [7]: $P_e(\alpha) = 0.5[e^{-A^2/(8\sigma^2)} + Q(A/(2\sigma))]$, where Q denotes the Gaussian Q function. However, due to a number of simplifying assumptions made in the derivation of [7] the final expression is somewhat inaccurate for high levels of noise, as demonstrated in Fig. 3b where it is plotted against the more complex but exact result of (8) and the narrowband empirical BER.

As opposed to indirectly using a chaotic signal to modulate the sinusoidal carrier within the chaos based ASK–OOK system, it is also possible to use a chaotic signal directly to represent a bit 1 and no signal to represent a bit 0. Such a system, termed chaotic on off keying (COOK), was proposed and investigated in [12]-[14]. However, unlike sinusoidal signals, chaotic signals generally do not have a constant envelope making a COOK system potentially more difficult and costly to implement.

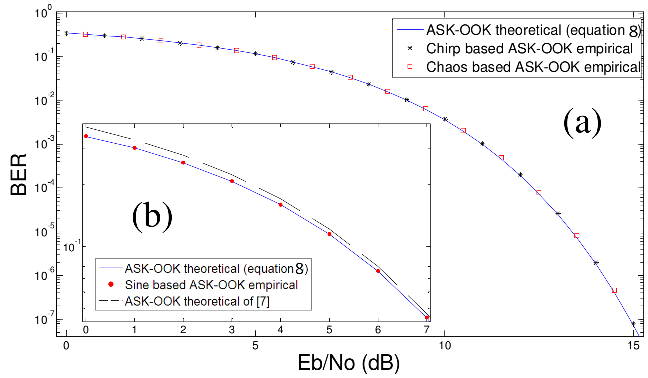

Figure 3. (a). Theoretical and empirical BER curves of the newly proposed broadband systems. (b). Margin of error within the theoretical BER of [7].

III. Chirp Based ASK-OOK System

By replacing the chaos based carrier signal by an LFM chirp signal, a novel broadband ASK–OOK system is proposed here. Its novelty over the chirp based spread spectrum OOK system of [6] is in the envelope detector receiver architecture, which is simpler and more cost effective than the power detector architecture of [6] that was empirically investigated in the human body channel. The power detector architecture involves squaring and integration of the received signal, as opposed to the envelope detector architecture which simply samples the constant envelope, resulting in a lower implementation cost. As for the chaos based system, it was found here that the decision variables of the proposed system are also of Rayleigh and Rician distributions. Furthermore, as the energy of an LFM chirp signal is also equal to $A^2T/2$ [9], resulting in an average energy of a bit of $E_b = A^2 T_b / 4$, it is readily verifiable by repeating the derivation presented in (6) to (8) that the probability of error of the novel chirp based system is also governed by (8). The result is confirmed in Fig. 3a by an exact match between the empirical BER curve and the theoretical result of (8).

IV. BER Performance and Optimisation in the AWGN Channel with Narrowband Interference

This section presents the BER performance of the narrowband sinusoidal and the two novel broadband systems when subjected to the sinusoidal narrowband interference. The novel chaos based system is then optimised to demonstrate a further improvement in the BER performance.

A. *BER performance of the ASK-OOK systems*

The BER results for the signal to interference ratios (SIR) of 20, 16, 12, 10, 8 and 6 dB are plotted in Fig. 4 from where it can be observed that although the narrowband and the proposed broadband ASK–OOK systems exhibit matching performance in the AWGN channel only, the broadband systems exhibit superior performance at all levels of interference.

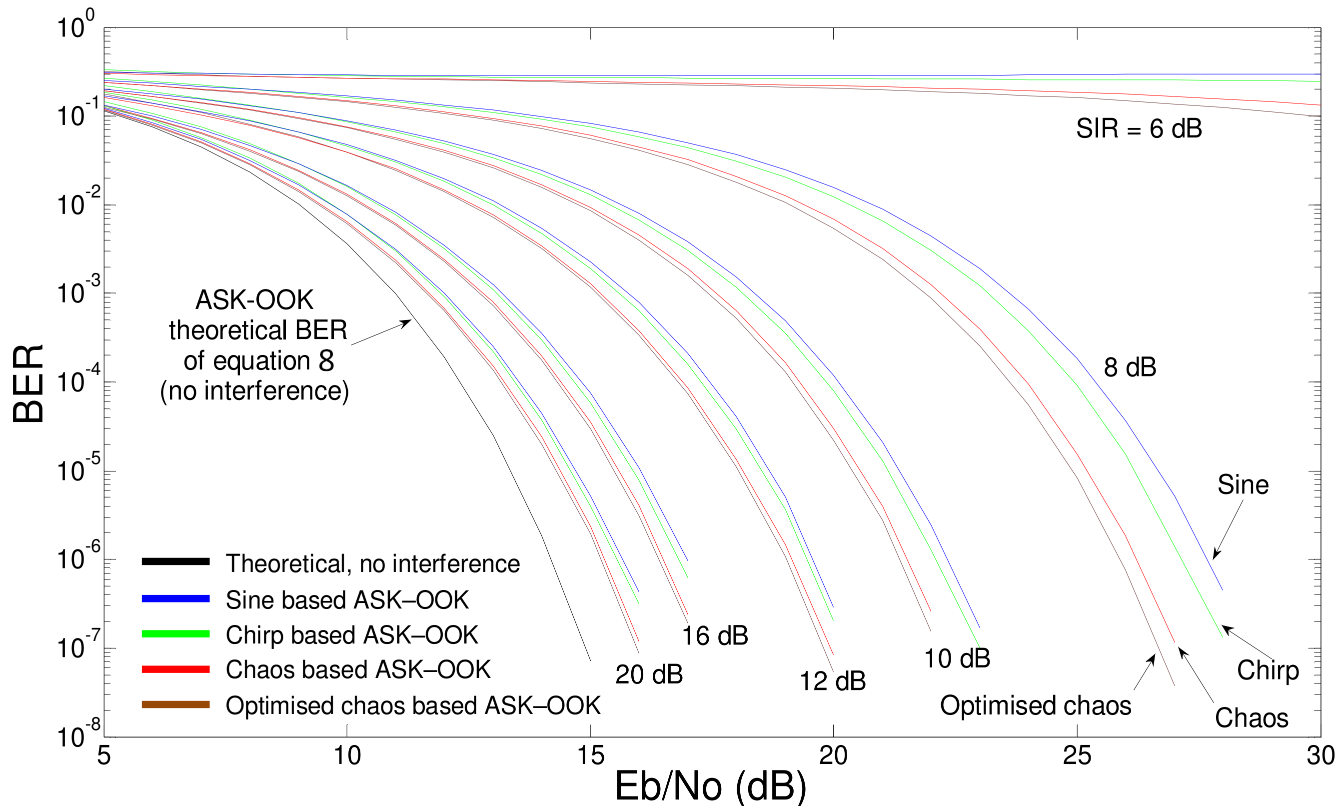

Figure 4. Empirical BER of the ASK–OOK systems for varying SIR levels.

The newly proposed broadband chirp based ASK–OOK system exhibits an increasing BER improvement over the narrowband system with the decreasing SIR. A further similar, but more notable, improvement over the narrowband sinusoidal and the broadband chirp based system is exhibited by the novel broadband chaos based system. For instance, at the SIR of 12 dB, and the BER level of 10^{-4}, an improvement of approximately 0.5 and 0.75 dB can be observed in favour of the chaos based system when compared to the chirp and narrowband sinusoidal systems, respectively. The improvement increases to approximately 1 and 1.5 dB at the SIR level of 8 dB. The bandwidth of the chirp carrier signal was kept the same as that of the chaos based carrier signal while the narrowband interference tone was kept near the centre frequency and within the system bandwidth R_b. For the narrowband sinusoidal ASK–OOK system, the interference tone was generated at the carrier frequency.

B. Optimisation of the novel chaos based ASK-OOK system

In [5], chaos based signals were used for radar applications where broadband chaos based radar pulses were optimised for detection of specific targets. In contrast to an LFM chirp signal where only a single unique signal can be generated in a given bandwidth, a chaotic system can theoretically produce an infinite number of chaotic signals and therefore also chaos based signals by varying its parameters or initial conditions. By producing a large number of different chaos based signals, Carroll showed [5] that it is possible to find a particular chaos based signal that yields a high signal reflection from one arbitrary radar target and a low signal reflection from some other arbitrary radar target. This was achieved by optimising chaos based signals for a given radar target, or a set of targets, whose reflection characteristics are known in advance. The optimisation of the chaos based radar model was achieved by employing the downhill simplex or Nelder–Mead algorithm [15]. Downhill simplex algorithm determines the minimum of a given equation, termed minimisation equation. In case of the chaos based radar optimisation problem the minimisation equation of [5] was based on minimising the reflection of one radar target with respect to another.

Taking the lead of [5], it is now demonstrated that the BER performance of the proposed chaos based ASK–OOK system of Section II can be further improved by optimising chaos based signals for a given level of narrowband interference. As opposed to minimising reflections from radar targets, the downhill simplex algorithm was used here to minimise the BER of the communication system. Optimisations were performed for each SIR level investigated at an *Eb/No* ratio corresponding to the BER level of 10^{-4} of a non optimised chaos based ASK–OOK system. Once an optimisation for a given SIR level was complete, the system was evaluated with the determined

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optimum chaos based carrier for a range of *Eb/No* ratios and the empirical BER curve obtained. The optimisations were started off with an initial random set of parameters that produce a non optimised chaotic signal of (3) and thus also a chaos based signal of (1). Upon evaluating the BER for the initial set of parameters, the downhill simplex algorithm varied the parameters and re-evaluated the BER. The process was repeated a large number of times until a smallest local minimum (optimum) BER value was determined. The optimisations were all nonlinear resulting in many local minima (as opposed to a definite global minimum), of which some had similar magnitudes. Nonetheless, the astringency of the algorithm may be improved by starting the algorithm execution with a favourable initial set of chaotic parameters. However, again, as the process is nonlinear, there is no rule on how to choose initial chaotic parameters that may enhance astringency.

An advantage of the downhill simplex algorithm over some other optimisation algorithms is that it does not require derivatives [15] what reduces its complexity. Other algorithms may also be employed to try to further improve the BER performance [16][15]. However, this is beyond the scope of this paper and will not be investigated here.

The optimised empirical BER curves for the varying SIR levels are plotted in Fig. 4 on the same set of axes as the non optimised curves. From the plots it can be observed that the improvement in BER performance of the optimised over non optimised chaos based ASK–OOK system ranges from less than 0.1 to approximately 0.5 dB at different SIR levels. Therefore, although the observed improvements are less significant than those of subsection IV-A, they further widen the improvement margin over the traditional narrowband system and demonstrate that the proposed chaos based ASK–OOK system's BER performance can be further improved through an optimisation process.

V. CONCLUSIONS

In this paper, two novel broadband chaos and chirp based ASK–OOK communication systems were proposed. Their theoretical probability of error expression was derived and confirmed by an exact match with the corresponding empirical BER simulations. It was shown that both of the proposed novel broadband ASK–OOK systems exhibit superior BER performance to the narrowband system in the presence of narrowband interference, while also exhibiting a matching performance in the AWGN channel only. The novel chaos based system was shown to exhibit the best BER performance with interference in the system, providing an improvement of up to 1.5 dB. Such a find is of particular importance for the ASK–OOK systems, which are traditionally known to offer little resistance to interference. Furthermore, it was demonstrated that the newly proposed chaos based ASK–OOK system can be optimised using the downhill simplex algorithm to further improve its BER performance by up to 0.5 dB in the presence of narrowband tone interference.

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