GENERALIZED CORRELATION-DELAY-SHIFT-KEYING SCHEME FOR NONCOHERENT
CHAOS-BASED COMMUNICATION SYSTEMS

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ABSTRACT
In this paper, we propose a generalized correlation-delay-shift-keying (GCDSK) scheme for noncoherent chaos-based communications. In the proposed scheme, several delayed versions of a chaotic signal are first produced. Some of them will be modulated by the binary data to be transmitted. The delayed signals will then be added to the original chaotic signal and transmitted. At the receiver, a simple correlator-type detector is employed to decode the binary symbols. The approximate bit error rate (BER) of the GCDSK scheme is derived analytically based on a Gaussian approximation. Simulations are performed and compared with the noncoherent correlation-delayshift-keying (CDSK) and differential chaos-shift-keying (DCSK) modulation schemes. The effects of the spreading factor, length of delay and the number of delay units on the BER are fully studied. It is found that GCDSK can achieve better BER performance than DCSK under reasonable bit-energy-to-noise-power-spectral-density ratios.

1. INTRODUCTION
Noncoherent communication schemes, which do not require the reproduction of the chaotic signals at the receiving end, are more feasible in practice [1]–[3]. The correlation delay-shift-keying (CDSK) scheme is one of the noncoherent detection schemes, which is similar to the DCSK scheme in that a reference chaotic signal is embedded in the transmitted signal [3]. Unlike in DCSK [2], however, the reference signal and the information-bearing signal are now added together with a certain time delay in CDSK. As a consequence, each transmitted signal sample includes one reference sample and one information-bearing sample, and the transmitted signal sample is never repeated. Since no individual reference signal is sent, the bandwidth efficiency is improved. Moreover, by eliminating the switch required to perform the switching between the reference chaotic signal and information-bearing signal in the DCSK system, CDSK allows a continuous operation of the transmitter. Also, the transmitted signal is more homogeneous and less prone to interception. However, because the sum of two chaotic signals is sent, more uncertainty (interference) is produced when the received signal correlates with its delayed version at the receiving side. Therefore, the performance of CDSK is worse than that of DCSK.

In this paper, we propose a generalized CDSK (GCDSK) scheme. The transmitted signal is composed of a reference chaotic signal and a number of delayed chaotic signals, some of which are modulated by the data being sent. Such a construction of the transmitted signal allows the transmission of more than one reference signal and more than one information-bearing signal simultaneously. The useful signal component, as well as the interference component, will be enhanced at the receiving side. We show that with an appropriate choice of system parameters, the bit error performance of the proposed system improves over the CDSK scheme. The system also inherits the merits of the CDSK system such as being switchless and allowing continuous operation of the transmitter.

2. GENERALIZED CORRELATION-DELAY-SHIFT-KEYING (GCDSK) SCHEME

2.1. Transmitter Structure
We propose a generalized CDSK (GCDSK) communication system, as shown in Fig. 1. The transmitter contains a chaotic signal generator and \((M−1)\) delay blocks. We assume that \(M>2\) because when \(M=2\), the GCDSK system degenerates to the CDSK system. Denote the minimum delay and the \(l\)th transmitted symbol by \(L\) and \(d_\ell\) respectively. Assume that “+1” and “−1” are transmitted with equal probability. First a chaotic signal, denoted by \(\{x_k\}\), is generated in the transmitter. The chaotic signals with delays \(L, 3L, 5L, \ldots\) are modulated by the data sequence \(\{d_\ell\}\), whereas the signals with delays \(2L, 4L, 6L, \ldots\) are unmodulated. Finally, the transmitted signal is formed by adding the original chaotic signal and all the delayed signals. Denote the spreading factor by \(\beta\), i.e., \(\beta\) chaotic signals \(s_k\), are sent within one bit duration. During the \(l\)th bit duration, i.e., for time \(k= (l−1)\beta+1, (l−1)\beta+2, \ldots, l\beta\), the transmitted signal is given by

\[
S_k = \begin{cases} 
\sum_{m=0}^{M-2} x_{k-2mL} + d_\ell \sum_{m=0}^{M-2} x_{k-(2m+1)L} & \text{if } M \text{ is even} \\
\sum_{m=0}^{M-2} x_{k-2mL} + d_\ell \sum_{m=0}^{M-2} x_{k-(2m+1)L} & \text{if } M \text{ is odd} 
\end{cases}
\]

(1)

where in each case, the first and second terms represent summation of all the unmodulated and modulated chaotic signals, respectively.

2.2. Receiver Structure
We assume an additional white Gaussian noise (AWGN) channel. The received signal, denoted by \(r_k\), is given by \(r_k = s_k + \xi_k\) where \(\xi_k\) denotes the AWGN signal with zero mean and variance...

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2.2.1. Gaussian-Approximated BERs

In our study, we make use of the Chebyshev map of degree 2 to generate the chaotic signal. The map is given by

\[ x_{k+1} = 2x_k^2 - 1 \]  

(10)

and its correlation properties have been reported previously [5, 6]. Assuming that the chaotic signal \( \{x_k\} \) is stationary, it is readily shown that for a given transmitted symbol \( d_i \), the mean value of the correlator output equals

\[ E[y_l | d_i] = d_i(\beta - L)(M - 1)P_s \]  

(11)

where \( E[\cdot] \) represents the expectation operator and \( P_s = E[x_k^2] \). If the conditional correlator output follows a Gaussian distribution, the approximate bit error rate for the GCDSK system can then be derived analytically and is given by

\[
\text{BER}_{\text{GCDSK}} = \frac{1}{2} \text{Prob}(y_l \leq 0 | (d_i = +1)) + \frac{1}{2} \text{Prob}(y_l > 0 | (d_i = -1)) \\
= \begin{cases} 
\frac{1}{4} \text{erfc} \left( \frac{(\beta - L)(M - 1)P_s}{\sqrt{2\text{var}[y_l | (d_i = +1)]}} \right) \\
+ \frac{1}{4} \text{erfc} \left( \frac{(\beta - L)(M - 1)P_s}{\sqrt{2\text{var}[y_l | (d_i = -1)]}} \right) & \text{when } L = 1 \\
\frac{1}{2} \text{erfc} \left( \frac{(\beta - L)(M - 1)P_s}{\sqrt{2\text{var}[y_l | (d_i = +1)]}} \right) & \text{when } 2 \leq L < \beta 
\end{cases}
\]  

(12)

where \( \text{erfc}(\cdot) \) represents the complementary error function [5]. Due to the limitation of space, the derivation of the \( \text{var}[y_l | d_i] \) is not described in this paper.

3. RESULTS AND DISCUSSIONS

In this section, we present our findings on the bit error performance of the GCDSK system. We denote the average bit energy by \( E_b \) which can be readily shown equal to

\[ E_b = \beta M P_s. \]  

(13)

For various average-bit-energy-to-noise-psd \( (E_b/N_0) \) ratios, we simulate the GCDSK system and record the BERs. Also, we compute the approximate BERs using (12). We then compare our results with those derived from the CDSK and DCSK systems whenever appropriate.

3.1. Effect of delay \( L \)

First, we investigate the effect of the delay \( L \) on the bit error performance. Figure 2 plots the BER of the CDSK system together with that of the GCDSK system with \( M = 4 \) and 6. A spreading factor \( \beta \) of 100 is used. It is observed that the bit error performance for the GCDSK system degrades as the delay \( L \) increases. As stated in Section 2.2, the correlator in the GCDSK receiver computes the sum of \((\beta - L)\) terms before deciding upon whether the received symbol is a “+1” or “−1”. Hence, the correlator output becomes more unreliable when the number of terms reduces due to an increase in \( L \), thereby increasing the BER. For the CDSK system, the number of the terms used in the correlator block is fixed at \( \beta \) and is independent of the delay \( L \). Therefore, the bit error performance of the CDSK system is found to be unaffected by the delay \( L \). Comparing the CDSK and GCDSK systems, it can be observed that for the same \( E_b/N_0 \), the GCDSK system outperforms the CDSK system with delay values up to 50.

3.2. Effect of the number of delay blocks

Note that the number of delay blocks in the transmitter side equals \( (M - 1) \). In Fig. 3, we plot the simulated BER against \( M \). (Note that the CDSK system corresponds to the case where \( M = 2 \).) A spreading factor \( \beta \) of 100 is used. It is shown that for a fixed \( E_b/N_0 \) value, the BER reaches an optimal value at a certain value of \( M \). Specifically, when \( M \) increases, the average bit energy and the detected signal component given by (13) and (11), respectively, increase initially. Although the intra-signal interference and the noise power also go up for a given \( E_b/N_0 \), there is a net improvement in the signal quality initially, thereby improving the BER. As
the value of \( M \) is further increased beyond the optimal point, the percentage increase in the detected signal component is overshadowed by the degradation due to intra-signal interference and noise. Therefore, the BER starts to degrade for large values of \( M \).

3.3. Comparison of the simulated and Gaussian-approximated BERs

Figure 4 compares the simulated and Gaussian-approximated BERs for the GCDSK system. A spreading factor of 100 is used. For the GCDSK system with \( M = 6 \), the discrepancy between the simulated and Gaussian-approximated BERs is quite significant when \( E_b/N_0 \) is large. When we analyse the statistics of the correlator output from the simulations, it is found that the conditional means and variances match with those derived in this paper. However, the distribution of the conditional correlator output does not follow a Gaussian distribution.

3.4. Comparison with DCSK system

In Fig. 5, the simulated BERs are plotted again for the CDSK, GCDSK and DCSK systems. \( \beta = 100 \) is used for all systems and a delay of \( L = 1 \) is employed for the CDSK and GCDSK systems. It is found that the CDSK system gives the worst BER and is approximately 2 dB worse than the DCSK scheme. For the GCDSK scheme, the BERs are about the same as the DCSK scheme and are better for \( E_b/N_0 \) values below 16 dB. Furthermore, we find that a simple Gaussian approximation is not sufficient to model the conditional correlator output at the receiver end. Hence, a more accurate model should be further investigated. Finally, compared with the CDSK and DCSK systems, the GCDSK system has the highest hardware requirement because of the additional delays and multipliers.

4. CONCLUSIONS

In this paper, we develop and study in detail a generalized correlation-delay-shift-keying (GCDSK) scheme for noncoherent chaos-based digital communications. We also compare the bit error rate (BER) of the proposed system with two previously studied noncoherent chaos-based communication schemes, namely, the correlation-delay-shift-keying (CDSK) scheme and the differential chaos-shift-keying (DCSK) scheme. Results show that the CDSK scheme gives the worst BER and is approximately 2 dB worse than the DCSK scheme. For the GCDSK scheme, the BERs are about the same as the DCSK scheme and are better for \( E_b/N_0 \) values below 16 dB. Furthermore, we find that a simple Gaussian approximation is not sufficient to model the conditional correlator output at the receiver end. Hence, a more accurate model should be further investigated. Finally, compared with the CDSK and DCSK systems, the GCDSK system has the highest hardware requirement because of the additional delays and multipliers.

5. REFERENCES