PERFORMANCE ANALYSIS OF CHAOTIC COMMUNICATIONS IN COOPERATIVE CELLULAR SYSTEM

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Abstract — The Differential Chaos Shift Keying (DCSK) modulation and demodulation is designed and simulated. The DCSK cooperative communication system for two users is proposed in this paper. The single relay cooperative network with amplify-and-forward relay is investigated in DCSK system according to two cooperation protocols, namely, conventional cooperation. Simulation results demonstrate that, through a conventional cooperation mechanism, the DCSK-CC system has better bit error rate. In addition, BER performance of DCSK in cooperative scenario is analyzed over a Rayleigh fading channel. Improved BER rates and diversity gains are the products of employing the above suggested techniques.

Keywords — Bit error rate (BER), DCSK, Multiple access, Diversity gain.

I. INTRODUCTION

Chaotic signals are a periodic, random-like signals derived from nonlinear dynamical systems. In the continuous time domain, chaotic signals are generated by ordinary differential equations whereas in the discrete time domain, they can be produced by iterative maps. Chaotic signals are also characterized by their impulse like autocorrelation and low cross correlation properties. Furthermore, a large number of chaotic carriers can be produced easily as a consequence of the sensitive dependence upon initial conditions and parameter variations. Moreover, chaotic signals are distinguished by their inherent wideband attribute. Thus, when chaotic signals are used as wideband carriers to convey information, they offer potential advantages that are accomplished by conventional spread spectrum communication systems, such as difficulty of uninformed detection and mitigation to multipath fading. Thus, chaos can provide a low cost and versatile technique for spread spectrum communications.

In a wireless network, system performance degrading is mainly attributed to signal fading and intersymbol interference (ISI) arising under multipath propagation environments. In general, signal fading can be mitigated by using a diversity technique.

In this paper, the two-user cooperative diversity technique is introduced into the DCSK system. The Walsh code sequences with excellent cross-correlation characteristics are adopted as user multiple access. The proposed system obtains cooperative diversity gain using a simpler AcR.

II. CHAOS BASED DIGITAL COMMUNICATIONS

In conventional digital communication systems, each symbol to be sent is represented by a piece of sinusoidal signal, which is periodic by nature. In chaos-based digital communication systems, each symbol is now denoted by a segment of chaotic signal, which is a periodic. Therefore, even if the same symbol is being sent repeatedly, the chaotic signals representing the same symbol are never the same. The chaos-based digital communication systems can be categorized into those that require the regeneration of chaotic carriers at the receivers, namely coherent systems, and those that do not have such a requirement, namely non-coherent systems. On the other hand, non-coherent systems are more practical. In the following, one of these digital communication schemes called DCSK based on chaos is presented.

A. Chaotic Signal Generation

Edward Lorenz has also an important place in the history of chaos. In the sixties he developed computer models. He made a lot of calculations to six decimal places. When he rounded off these numbers to three decimal places, the result was astonishing. In the beginning the old and new calculations coincided, but after some time the results were totally different. The conclusion is that the small different in the start position can lead to large differences in the final result. The chaotic signal can be generated by two types of domain.

In the continuous-time domain, chaotic signals are generated by ordinary differential equations whereas in the discrete-time domain, they can be produced by iterative maps. The iterative map is further classified into two types as discussed below.

1) Logistic Map: The chaotic signal which is generated by this map function, which has equation below:

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

where \( x_k \) – previous output

This mapping function uses its previous output as present input. The initial value is different for
generating different chaotic sequences. The value of \( x_k \) is assumed to be 0.1 and 0.4. It is important to note that \( x_k \neq 0, \ 0.5, \ 1 \).

2) Cubic Map: The chaotic signal which is generated by this map function, which has equation below:

\[
x_{k+1} = 4x_k^3 - 3x_k
\]  

where \( x_k \) – previous output

This mapping function uses its previous output as present input. The initial value is different for generating different chaotic sequences. It is important to note that \( x_k \neq 0 \) and 1

**B. Principle of DCSK**

When the CSK signals are decoded based on the estimation of the bit energy, the threshold of the detector should shift with the noise level. Otherwise, lots of errors would occur. To overcome this issue, differential chaos-shift-keying (DCSK) modulation scheme has been proposed. Fig. 1 shows the block diagram of a DCSK system.

In DCSK uses a chaotic signal as the carrier, with a differential shift keying modulator, for transmission. The chaotic signal is generated by a chaotic mapping method, and the simple Logistic chaotic map is chosen here for implementation. The binary DCSK modulation unit transmits a reference segment of the chaotic signal in the first half of the symbol duration, and repeats or reverses the segment in the last half of the symbol duration, according to the digital information ‘1’ or ‘0’ respectively. The modulated signal is represented by two orthogonal basis functions \( g_1(t) \) and \( g_2(t) \) as follows.

**Fig.1 DCSK system block diagram (a) Transmitter (b) Receiver**

\[
s(t) = s_{m1}g_1(t) + s_{m2}g_2(t)
\]

\[
\begin{pmatrix}
s_{11} \\
s_{12}
\end{pmatrix} = (\sqrt{E_{b}}0)
\]

\[
\begin{pmatrix}
s_{21} \\
s_{22}
\end{pmatrix} = (0\sqrt{E_{b}})
\]

Here \( s(t) \) is modulated signal for transmission and \( E_{b} \) is the bit energy.

The two orthogonal basis functions are:

\[
g_1(t) = \begin{cases}
+c(t), & 0 < t < T_b/2 \\
+c(t - T_b/2), & T_b/2 < t < T_b
\end{cases}
\]

\[
g_2(t) = \begin{cases}
+c(t), & 0 < t < T_b/2 \\
-c(t - T_b/2), & T_b/2 < t < T_b
\end{cases}
\]

where \( T_b \) - bit duration, \( c(t) \) – chaotic signal.

In DCSK, each basis function consists of a reference and an information-bearing segment. The receiver can be implemented using a suboptimum autocorrelation receiver. In autocorrelation receiver, the observation signal is given by

\[
z = \int r(t)r(t - T_b/2)dt
\]

where \( r(t) \) – received signal into the autocorrelation receiver.

Recovery of the message is achieved by correlating the current signal with itself delayed by half of the symbol transmission period \( T_b/2 \). This approach results in the rejection of the noise encountered in the transmission channel and the recovery of the bit code transmitted.

**C. User Differentiation based on Walsh Code**

For a multiple user or non binary DCSK communication system, the orthogonal Walsh code sequences were adopted for implementation. Let \( W_n^a \) be a \( 2^n \) Walsh code sequence, \( n=0,1,2... \)

\[
W_1 = [+1]
\]

The second order Walsh code sequences are recursively constructed as follows.

\[
W_2 = \begin{bmatrix}
+1 & +1 \\
+1 & -1
\end{bmatrix}
\]

As a universal method, second-order Walsh code is used for binary DCSK and higher order Walsh code is employed for multiuser or non binary DCSK. For DS-SS multiple access, it specifies three conditions that must be met by a set of orthogonal sequences. The three conditions are (1) The cross correlation should be zero or very small. (2) Each sequence in the set has an equal number of 1s and -1s, or the number of 1s differs from the number of -1s by at most one. (3) The scaled dot product of each code should equal to 1.

**III. DCSK IMPLEMENTATION**

The basic chaos circuit for DCSK modulation is shown in Fig 2. The aim is to study the Chaos circuit in some detail. In the first part of this project we will make computer simulations of its behavior.

**D. Modeling the Circuit**

The circuit is modeled assuming ideal linear characteristics for the capacitors, the resistors and the inductance. Only the diode is assumed to have a modest static nonlinearity consisting of a piecewise linear characteristic. Let us take as state variables. (1) \( V_1 \): the voltage over the capacitor \( C_1 \), (2) \( V_2 \): the voltage over the capacitor \( C_2 \) and (3) \( I_1 \): the current through the inductance \( L_1 \).

If we moreover assume that all components, except for the diode, have linear ideal characteristics, then Kirchhoff’s law gives us the model.
\[ C_1 V_1 = \frac{1}{R_1} (V_2 - V_1) - f(V_1) \]  
\[ C_2 V_2 = \frac{1}{R_1} (V_1 - V_2) - f(V_2) \]  
\[ L_1 I = -R_1 I - V_2 \]  

where \( C_1 \) and \( C_2 \) are the conductors, \( L_1 \) is the constant value of the coil, \( R_{11} \) is the changeable resistor, \( R_3 \) is the internal resistance of the coil and \( f \) is the non-linear voltage-current characteristic of the chaos diode.

\[ \frac{\text{COMPONENT SPECIFICATIONS CHAOS CIRCUIT}}{\text{T A B L E} 1} \]

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_1 )</td>
<td>1 uF</td>
</tr>
<tr>
<td>( L_1 )</td>
<td>1 H</td>
</tr>
<tr>
<td>( L_2 )</td>
<td>10 H</td>
</tr>
<tr>
<td>( R_1 )</td>
<td>1 T</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>2000</td>
</tr>
<tr>
<td>( R_3 )</td>
<td>1 kΩ</td>
</tr>
<tr>
<td>( R_4 )</td>
<td>4 kΩ</td>
</tr>
</tbody>
</table>

With the above specifications, the circuit compares very well with what the simulation results predict. The components are chosen in such a way that the frequencies in the voltages over \( C_1 \) and \( C_2 \) also fit in the audio range. Hence the results are not only interesting on an oscilloscope but also audible when connected to an audio amplifier.

### F. Multiple Access DCSK

DCSK is a modulation scheme for chaotic carrier signals. It was designed especially for multiple access applications such as in a cellular spread spectrum environment. The basic principle of MA-DCSK is extremely simple. Consider a MA-DCSK communication system with \( N \) users, as shown in Fig.

A discrete-time approach will be adopted in the following analysis. In the transmitter of the \( \text{ith} \) user, a pair of chaotic sequences, denoted by \( \{ x_0(i) \} \) and inverse of \( \{ x_0(i) \} \) are generated by a chaotic map with different initial conditions.

Assume that the mean value of each of the chaotic sequences is zero in order to avoid transmitting any dc component which is a waste of power. Denote the \( m^\text{th} \) transmitted symbol for the \( \text{ith} \) user by \( d_\text{m}^{(i)} \) and \( \sigma_i \) denotes the additive white Gaussian noise with zero mean and variance (power spectral density) \( N_0=2 \). Assume that synchronized versions of the chaotic signals \( \{ x_0(i) \} \) and inverse of \( \{ x_0(i) \} \) can be reproduced at the receiver. The detection essentially involves correlating the incoming signal with the locally regenerated chaotic signals and sampling the outputs of the correlators at the end of each symbol duration. The \( m^\text{th} \) decoded symbol for the \( j^{\text{th}} \) user is determined.

### IV. COOPERATIVE CELLULAR SYSTEM

Cooperative communication was introduced in using the scenario depicted in Fig.3.2 but with the relay...
terminal being another source. Both sources (associated partners) are also responsible for transmitting the information of their partners. It was assumed that the sources are working in full duplex mode, so that both sources are transmitting to the destination and receiving a noisy version of the partner’s transmission. Results in terms of ergodic achievable rate regions and outage probability of the cooperative and non cooperative transmission show the benefits of this scheme.

G. Two-User Cooperative Model

For exposition, consider a cellular system in which two mobiles are communicating with a base station. The channels between each user and the base station (the uplink channel) are independent, so are the channels between the two users (the inter-user channel). Due to the advantages of DCSK over frequency-selective channels, all channels are assumed to subject to static block frequency-selective fading; that is, the channel state remains constant during each cooperative period. It is assumed that a cooperative period is divided into broadcast phase and cooperative phase, denoted as odd period and even period, respectively. The transceiver model used is illustrated by Fig. 5.

![Fig. 5. Cooperative diversity protocols](image)

The two users cooperate by dividing the transmission of their N-bit code words into two successive time segments, or frames. In the first frame, each user transmits its own N1 bits through DCSK modulation to all available relays and the destination. Each partner as one relay also receives and amplifies the user's transmitted data. If the partner successfully amplifies the user's N1 bits within that frame, then it exploits them into N2 bits and modulates the N2 bits again in the second frame.

In this model, we consider two mobiles communicating to a destination terminal as shown in Fig. 3.3. Each mobile has its own information to be sent to the destination, denoted by \( W_i \), \( i = 1,2 \), with respect to mobile 1 and mobile 2. Moreover, each mobile also assists the other mobile to relay its signal, denoted by \( Y_i \), \( i = 1,2 \) corresponding to mobile 2 and mobile 1, respectively, to the destination. Clearly, the received signal \( Y_0 \) can achieve cooperative diversity because the transmitted signal \( X_{10} \), \( X_{20} \) in each mobile contains the information of both \( W_1 \) and \( W_2 \).

To be specific, the mathematical baseband model during one symbol period is

\[
Y_0 = K_{10} X_{1} + K_{20} X_{2} + Z_0 \quad (11)
\]

\[
Y_1 = K_{21} X_{2} + Z_1 \quad (12)
\]

\[
Y_2 = K_{12} X_{1} + Z_2 \quad (13)
\]

where \( \{K_i\} \) denotes the channel fading coefficients which remain constant during one symbol period, and \( Z_i = 0, 1, 2 \) are the AWGN in destination, mobile 1 and mobile 2, respectively. The received signal \( Y_0 \) should be able to isolate the signals \( W_1 \) and \( W_2 \) for signal recovering. For this purpose, the use of two orthogonal channels may be useful is shown in Fig. 6.

![Fig. 6 Channel model](image)

H. Amplify and Forward

The source terminal and destination terminal are denoted by \( S_s \) and \( D_d \), respectively, and we assume that the number of source terminals and destination terminals are equal to be \( Na \). The relay terminal is denoted by \( R_r \), where the number of the relay terminals is \( Nr \). This cooperative protocol follows the two phase scheme again. In phase I, the source nodes transmit the source signals to the relay nodes. In phase II, the relay nodes amplify and forward the received signal from source nodes to destination nodes. The system model for AF cooperative algorithm illustrated in Fig. 7. The transmitted signals of these source terminals are denoted by a signal vector \( S = [s_1; s_2] \) whose element \( s_i \).

![Fig. 7 System model of AF cooperative algorithm](image)

The signal received by the relay was attenuated and needs to be amplified before it can be sent again. In doing so the noise in the signal is amplified as well, this is the main downfall of this protocol. The incoming signal is amplified block wise. Assuming that the channel characteristic can be estimated perfectly, the gain for the amplification can be calculated as follows. The power of the incoming signal (2.4) is given by

\[
E \left[ |v_i|^2 \right] = E \left[ |r_{i1}|^2 \right] E \left[ |r_{i2}|^2 \right] + E \left[ |r_{i3}|^2 \right] \quad (14)
\]

\[
E \left[ |v_{i}|^2 \right] = |r_{i1}|^2 + 2 \sigma_{1,1} \quad (15)
\]
where s denotes the sender and r the relay. To send the data with the same power the sender did, the relay has to use a gain of

$$\beta = \frac{4}{\sqrt{\left|h_s^2\right| + \left|h_r^2\right| + 2\sigma^2}}$$  \hspace{1cm} (16)

This term has to be calculated for every block and therefore the channel characteristic of every single block needs to be estimated.

V. RESULTS AND DISCUSSIONS

Simulations were performed to analyze the system performance with and without cooperation under worst case channel conditions. The performance comparisons of with and without cooperation of the DCSK cellular system is analyzed in terms of BER Vs $E_b/N_0$.

I. DCSK Implementation Results

The DCSK modulation and demodulation is done through Chaos circuits (see Fig. 2 and Fig. 3) is shown in Fig. 8. Here, the data is generated by using the signal generator with input of $5V_{pp}$ as shown in Fig. 8(a). Fig. 8(b) shows the chaotic carrier signal. This can be mathematically described in equations (8),(9),(10). The obtained result of DCSK modulation is shown in Fig. 8(c), green color waveform represents the information and yellow represents the DCSK modulation output. The binary DCSK modulation unit transmits a reference segment of the chaotic signal in the first half of the symbol duration, and repeats or reverses the segment in the last half of the symbol duration, according to the digital information ‘1’ or ‘0’ respectively. The demodulation part is recovered through implementing a simple low pass filter. The main function of low pass filter is to extract the original information from the modulated signal by filtering the high frequency signal and to avoid distortion and minimize the effect of noise. The demodulated output waveform is shown in Fig. 8(d), green represents the information and yellow represents the demodulated output.

![Fig. 8 DCSK modem hardware implementation results](Image)

(a) Data (b) Chaotic carrier (c) Modulation (d) Demodulation

J. DCSK Without Cooperative Communication

The simulation results of DCSK without cooperation is shown in Fig. 9. The data is randomly generated. In the continuous time domain, chaotic signals are generated by ordinary differential equations whereas in the discrete time domain, they can be produced by logistic map (see eq. (1)).

![Fig. 9 BER performance of DCSK for non cooperative scenario](Image)

Fig. 9 DCSK modulation and demodulation waveforms for a single user

The modulated output is allowed to experience Rayleigh fading. Fig. 10 shows the BER performance DCSK non cooperative scenario. The performance enhances as $E_b/N_0$ increases. The bit error rate of $10^{-2}$ is obtained at $E_b/N_0$ as 9.5dB .The performance can be further improved by using cooperative scenario combined with chaotic communications.

![Fig. 10 BER performance of DCSK for non cooperative scenario](Image)

C. DCSK With Cooperative Communication

The DCSK modulation and demodulation for two users is shown in Fig. 11 and Fig. 12. To eliminate the inter-user interference completely, Koloumban et al. proposed the introduction of Walsh codes into the multiple access DCSK system. Second order Walsh code is used for binary DCSK is given in eq. (7).
CONCLUSION AND FUTURE WORK

In this paper, hardware and software implementation of DCSK has been accomplished and its performance is tested. The performance of cellular system employing chaotic communications without cooperation was evaluated. By using the best two user cooperative algorithm, diversity gain is analyzed over multipath fading channels in a cooperative scenario. If diversity gain is more, then the performance of a cellular system enhances drastically.

The simulation results show that the DCSK cellular system without cooperation provides a signal to noise ratio of about 9.5dB at a bit error rate of $10^{-2}$ and DCSK cellular system with cooperation provides a signal to noise ratio of 7.6 dB at a bit error rate of $10^{-2}$. The performance of with and without cooperation has been compared. Here the diversity gain of 1.9 dB is achieved at the bit error rate of $10^{-2}$ which is comparatively better than the non cooperative scenario.

To enhance the data security of DCSK system, the permutation transformation which destroys the similarity between data and the reference samples has to be introduced. The problems of multi-relay selection for multi-stream cooperative MIMO systems with M relay nodes has to yet considered and analyzed.

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