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Error-Correcting Scheme Without Redundancy Code Using Chaotic Dynamics for Noncoherent Chaos Communications

(Invited Paper)

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***Abstract*— This paper proposes a novel error-correcting scheme for noncoherent chaos communications. By using the chaotic dynamics which is one of characteristics of chaos our proposed scheme is possible to operate the error-correcting without the physical redundant code. As results of computer simulations, we confirm about 1–2 dB gain in BER performance as compared with the conventional noncoherent chaos communications.**

I. Introduction

Chaos communication systems are an interesting topic in the field of engineering chaos [1]– [4]. Especially, many researchers focused on the development of noncoherent detection systems which are demodulation techniques using signals modulated by chaos only or chaotic systems. Differential chaos shift keying (DCSK) [1] and the optimal receiver [2] are well-known typical noncoherent systems. Moreover, it is also important to develop a suboptimal receiver with performance equivalent to or similar to the optimal receiver using more efficient algorithms [3].

In our previous research, we proposed the suboptimal receiver using the shortest distance approximation [5]. Instead of calculating the PDF, the proposed suboptimal receiver approximates the PDF by calculating shortest distances between the received signal and the chaotic maps and performs detection of the transmitted symbol. As results of the computer simulations, we confirmed the validity of the proposed suboptimal receiver as an approximation method of the optimal receiver.

To improve the performance of the suboptimal receiver, we are concerned with an error-correcting scheme. Especially, we focus on characteristics of chaos to design an error-correcting method. Chaotic sequences obtained from a certain class of difference equations are non-periodic, sensitive to initial conditions and it is difficult to predict their future behavior using past observations. In other words, chaotic sequences are generated according to specific rules, i.e., the chaotic dynamics.

In this study, we focus on the chaotic dynamics and propose a novel error-correcting scheme. In our proposed system, two successive chaotic sequences are generated from the same chaotic map; the second sequence is generated with an initial value which is the last value of the first sequence. In this case, successive chaotic sequences having the same chaotic dynamics are created. This feature gives the receiver additional information to correctly recover the information data and thus improves the bit error performance of the receiver. In addition, as compared with general error correcting methods, our proposed scheme is possible to operate the error-correcting without the physical redundant code.

We carry out computer simulations and evaluate the performance of the proposed method.

II. System overview

We consider the discrete-time binary CSK communication system with the error correcting, as shown in Fig. 1. Detail of each block is described below.

In the transmitter, binary data are encoded by chaotic sequences generated by a chaotic map. In this study, we use a skew tent map which is one of simple chaotic maps, and it is described by Eq. (1)

$$x_{i+1} = \begin{cases} \dfrac{2x_i + 1 - a}{1 + a} & (-1 \leq x_i \leq a) \\[2ex] \dfrac{-2x_i + 1 + a}{1 - a} & (a < x_i \leq 1) \end{cases} \tag{1}$$

where a denotes a position of the top of the skew tent map. Our encoder is designed based on Chaos Shift Keying (CSK) which is a digital modulation system using chaos. Figure 2 shows our encoder for our error-correcting scheme. To perform the error correction at the receiver, K information bit are transmitted as K signal blocks $(0, 1, \cdots, j, \cdots, K-1)$, The encoder selects a chaotic signal generator according to the symbol. If the symbol “1” is sent, Eq. (1) is used, and if “0” is sent, the reversed function of Eq. (1) is used. Thus, the signal vector $\mathbf{S_j}$ is different for each symbol.

[When the symbol “1” is sent]

$$\mathbf{S_j} = (x_\alpha,\ f^{(1)}(x_\alpha), \cdots, f^{(i)}(x_\alpha), \cdots, f^{(N-1)}(x_\alpha)) \tag{2}$$

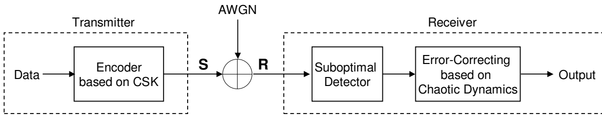

Fig. 1. Block Diagram of Discrete-Time Binary CSK Communication System.

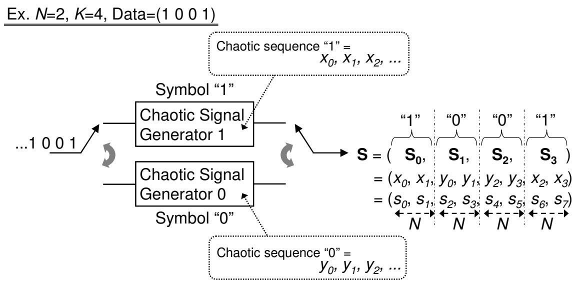

Fig. 2. Encoder based on CSK for error correction.

[When the symbol "0" is sent]

$$\mathbf{S_j} = (y_\alpha,\ g^{(1)}(y_\alpha), \cdots, g^{(i)}(y_\alpha), \cdots, g^{(N-1)}(y_\alpha)) \qquad (3)$$

where $f^{(i)}$ and $g^{(i)}$ are the function of the skew tent map for symbol "1" and "0", respectively, i is the iteration of f or g, $\alpha = N \times j$, x_j or y_j denotes the initial value of the jth symbol = "1" or "0" respectively, N is the chaotic sequence length per 1 bit. When K bit data is transmitted, the length of the data becomes $K \times N$. An initial value is chosen at random when beginning to make signal blocks and is different in each chaotic signal generator. In addition, the j-th sequence is generated from the initial value which is the end value of the former sequence with same symbol of j-th bit. As an example, we assume $N = 2$, $K = 4$ and the data are (1, 0, 0, 1) shown in Fig. 2. In this case, the transmitted signal vector **S** is given as follows.

$$\begin{aligned} \mathbf{S} &= (\mathbf{S_0}, \mathbf{S_1}, \mathbf{S_2}, \mathbf{S_3}) \\ &= (x_0, x_1, y_0, y_1, y_2, y_3, x_2, x_3) \\ &= (s_0, s_1, s_2, s_3, s_4, s_5, s_6, s_7) \end{aligned} \qquad (4)$$

As one can see, the initial value of the 4th symbol and 3rd symbol is generated by the end value of 1st symbol and 2nd symbol, respectively.

The channel distorts the signal and corrupts it by noise. In this study, noise of the channel is assumed to be the additive white Gaussian noise (AWGN). Thus, the received signals block is given by $\mathbf{R} = (r_0,\ r_1, \cdots,\ r_{KN-1}) = \mathbf{S} + AWGN$.

The receiver recovers the transmitted signals from the received signals and demodulates the information symbol. Also, the receiver performs the error correction in this study. Since we consider a noncoherent receiver, the receiver memorizes the chaotic map used for the modulation at the transmitter. However, the receiver never knows the initial value of chaos in the transmitter. Our proposed error-correcting method consists of the suboptimal detector and the error correction based on chaotic dynamics, as shown in Fig. 3. First of all, the receiver performs the noncoherent detection for each received block and demodulates each symbol. In this study, we apply the our suboptimal detection algorithm as the noncoherent detection [5]. After demodulation of each symbol, the receiver performs the error-correcting method. Here, we introduce the operation of our suboptimal detection.

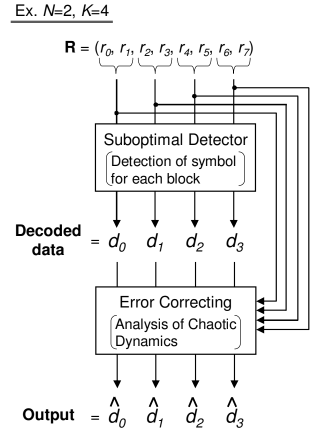

Fig. 3. Operation of proposed error-correcting method.

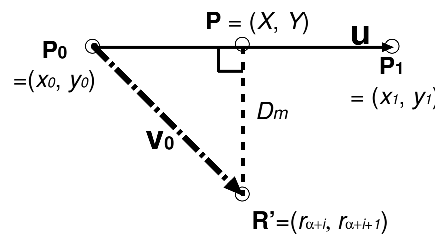

Fig. 4. Calculation of shortest distance.

Our suboptimal detection calculates the shortest distance between the received signals and the chaotic map in the N_d-dimensional space using N_d successive received signals (N_d : $2, 3, \cdots$). As an example, we explain the case of $N_d = 2$. In this case, we consider two successive signal samples $\mathbf{R}' = (r_{\alpha+i},\ r_{\alpha+i+1})$ as coordinate of chaotic map. To decide which map is closer to the point $\mathbf{R}'$ the shortest distance between the point and the map has to be calculated. Therefore, the receiver can calculate the shortest distance using the scalar product of the vector.

Any two points $\mathbf{P_0} = (X_0, X_0)$ and $\mathbf{P_1} = (X_1, Y_1)$ are chosen from each straight line in the N_d-dimensional space, as shown in Fig. 4. Using Fig. 4, the detector can calculate the point $\mathbf{P} = (X, Y)$ closest to $\mathbf{R}$ and the shortest distance D using the following equations.

$$\mathbf{P} = (X, Y) = (\mathbf{u} \cdot \mathbf{v_0})\,\mathbf{u} + \mathbf{P_0} \qquad (5)$$

$$\begin{aligned} D &= ||\mathbf{P} - \mathbf{R}'|| \\ &= \sqrt{(X - r_{\alpha+i})^2 + (Y - r_{\alpha+i+1})^2} \end{aligned} \qquad (6)$$

where

$$\begin{aligned} \text{unit vector } \mathbf{u} &= \frac{\mathbf{P_1} - \mathbf{P_0}}{||\mathbf{P_1} - \mathbf{P_0}||} \qquad (7) \\ \mathbf{v_0} &= \mathbf{R}' - \mathbf{P_0}\ . \qquad (8) \end{aligned}$$

In the case of 2-dimensional space, there are two straight lines in the space. Therefore, the minimum value in four distances is chosen as the shortest distance D_1 for symbol "1". In the same way, D of symbol "0" is chosen as D_0. We perform these operations until the last sample (i.e., $r_{\alpha+N-1}$) is included, and find their summations $\sum D_1$ and $\sum D_0$. Finally, we decide the decoded symbol as 1 (or 0) for $\sum D_1 < \sum D_0$ (or $\sum D_1 > \sum D_0$). The calculation of the shortest distance can be extended to N_d-dimensional space for $N_d \geq 4$.

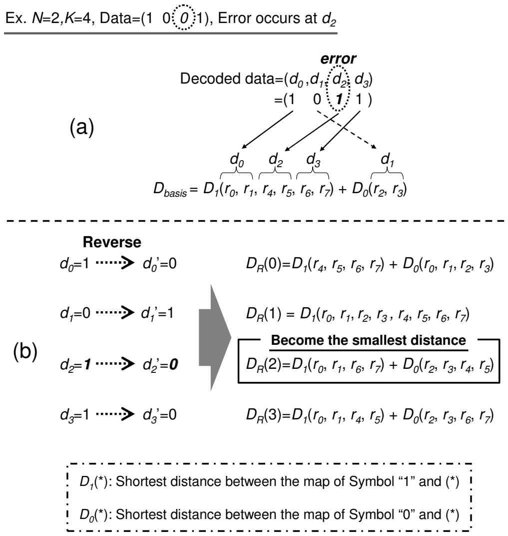

Fig. 5. Analysis of Chaotic Dynamics using Suboptimal Detection.

III. Error-correcting method without Redundancy code

In this section, we describe the error-correcting scheme without redundancy code. For ease of explanation, we use Fig. 5 and explain an operation of the proposed error-correcting scheme. Here, we use same assumption in the explanation of the encoder (Fig. 2). Also, we assume that decoded symbols become $(1, 0, 0, 1)$ and the detection error has occurred at the 2nd symbol (d_2), namely the case of 1 bit correction.

First of all, the receiver sorts the received signal samples based on decoded symbols and analyzes the chaotic dynamics of two sequences which are sorted according to decoded symbols, as shown in Fig. 5(a). If the receiver can detects symbols and sorts blocks correctly, we can obtain two successive chaotic sequences based on the chaotic dynamics. However, if the detection error is occurred when the receiver detects symbols, the sorted sequence mixes two chaotic sequences which differ in the chaotic dynamics. We focus on these characteristics of chaos for the error-correcting. For analyzing the chaotic dynamics, the receiver apply our suboptimal detection algorithm, i.e., the calculation of the shortest distance between the chaotic maps and two sorted received sequences. Thus, we define a reference distance D_{basis} as follows.

$$\begin{aligned} D_{basis} &= D_1(\text{Sequence of decoded symbol "1"}) \\ &+ D_0(\text{Sequence of decoded symbol "0"}) \end{aligned} \quad (9)$$

where $D_1(.)$ and $D_0(.)$ mean the shortest distance between the chaotic map of Symbol "1" and "0", respectively.

Next, we calculate the distance $D_R(j)$ for comparing with D_{basis}, where the subscript R means initial character of "Reverse". This equation means the shortest distance between sorted sequence when the j-th decoded symbol is reversed and the chaotic map corresponding to their sequences. Namely, we assume the detection error is occurred at j-th symbol and calculate $D_R(j)$. If the receiver can detects symbols and sorts blocks correctly, $D_R(j)$ becomes lager values as compared with D_{basis}. On the other hands, if the detection error is occurred, some of $D_R(0)$–$D_R(K-1)$ become smaller as compared with D_{basis}. The reason for changing the values is also to change combinations of the chaotic dynamics. Therefore, the receiver selects the smallest distance from D_{basis} and $D_R(j)$ and corrects an error.

For instance, Fig. 5(b) shows conceivable combinations of sorted sequences and calculates $D_R(j)$ when the detection error has occurred at the 2nd symbol. In this case, $D_R(2)$ becomes the smallest distance as compared with D_{basis} and other other $D_R(j)$. Thus, the receiver can determine that the detection error is occurred at the 2nd symbol.

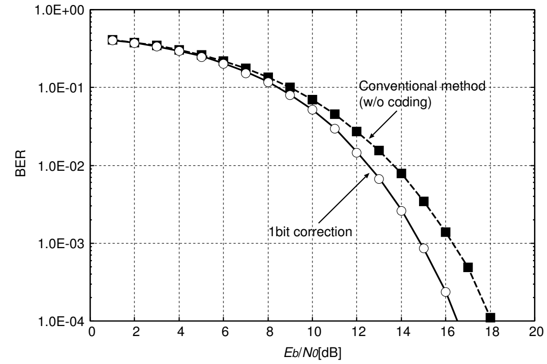

Fig. 6. BER performance ($K = 32$).

IV. Simulation Result

In this section, we evaluate the performance of the proposed error-correcting method. We carry out computer simulations and calculate a bit error rate (BER). The simulation conditions are as follows. In the transmitting side, we assume $K = 32$. The parameter of the skew tent map is fixed as $a = 0.05$. The chaotic sequence length per 1 bit is $N = 4$. For calculation of the shortest distance, we use 4-dimensional space, namely $N_d = N = 4$. Based on these conditions, we iterate the simulation 10,000 times and calculate BER, the accuracy rate and the computation time.

Figure 6 show the BER versus E_b/N_0 for $K = 32$. We plot the performance of the proposed error-correcting method and the performance of the conventional method, namely, the performance without the error-correcting method in Fig.6. From these figures, we can confirm that the advantage gained in BER performance of the proposed error-correcting method is about 1–2 dB compared to conventional method.

V. Conclusions

In this study, we have focused on the chaotic dynamics and proposed the error-correcting scheme without the redundancy code. As results, we have confirmed that the 1–2dB gain in error performance of the proposed method with $N = N_d = 4$.

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