Comparison of DCSK Receiver and Enhanced DCSK Receiver with Synchronization Error

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Abstract—Over the past decade, much research effort has been devoted to the study of communication using chaotic basis functions. Due to the low complexity in hardware implementation and low power consumption in chaotic signal generation, the chaotic signal is one of the possible candidate signals, applicable to both low rate Ultra-WideBand (UWB) systems and sensor networks. Among the modulation schemes using the chaotic signal, Differential Chaos Shift Keying (DCSK) is a robust non-coherent technique with respect to the implementation issue. However, Inter Symbol Interference (ISI) can induce the crucial performance degradation and synchronization error may destroy the orthogonality of the basis functions. Therefore, we present enhanced DCSK scheme and investigate the effect of the synchronization error on the performance by comparison with that of conventional DCSK.

I. INTRODUCTION

No necessity for carriers and the possibility for security in chaotic communications attract much interest in communication systems. Due to the easiness of generation for the chaotic signal, the chaos-based communication systems also have the low power consumption property. In order to utilize these advantages of the chaotic signal, many possible chaos-based communication schemes were evaluated and simulated both in AWGN channel and in multipath environment [1]-[6]. Among them, coherent detection schemes have difficulty in successfully recovering the chaotic basis functions at the receiver. Thus, non-coherent receiver may be more realistic candidate in chaotic communication systems. As a representative of the non-coherent receiver, Chaotic On Off Keying (COOK) was discussed in [1]. However, the disadvantages of COOK are that the dynamic range of the transmitted power level varies between zero and twice the average transmitted power level and that the optimum decision threshold for detection depends on the SNR. Therefore, Differential Chaos Shift Keying (DCSK) is possible alternative modulation scheme because its optimum threshold level for decision is always zero regardless of the SNR.

In general, the communication systems can achieve the maximum performance in AWGN only when the basis functions are orthonormal [7]. In chaotic systems, this requirement is satisfied over one bit interval only in the mean, i.e.,

\[
E\left[\int_{T_b} g_j(t)g_k(t)dt\right] = \begin{cases} 1, & \text{if } j = k \\ 0, & \text{otherwise} \end{cases}
\]  

(1)

where \(T_b\) is the bit duration and \(E[\cdot]\) denotes the expectation operator. In DCSK receiver, the approach to the auto- and cross correlation estimation problems was introduced in [1]. However, even though the orthogonality of the basis functions is assured in DCSK systems, the symbol synchronization error may destruct the orthogonality of the basis functions and deteriorate the system performance. Moreover, DCSK receiver is also vulnerable to the effect of multipath causing the Inter Symbol Interference (ISI).

In this paper, we propose enhanced DCSK scheme, which keeps satisfying the orthogonality of the basis functions, even in case of the symbol timing mismatch. The simulation results show both the improved system performance and the effect of the synchronization error.

Section II describes the system structure for two DCSK schemes. In section III, we present the simulation results of conventional DCSK and enhanced DCSK scheme in various environments including the case of the synchronization mismatch. Finally, we reach the conclusion about the enhanced DCSK scheme in section IV.

II. SYSTEM DESCRIPTION

In order to describe the system configuration of the proposed DCSK transceiver, we briefly introduce the conventional DCSK and explain the difference between two systems. Moreover, we conceptually examine the characteristics of enhanced DCSK scheme with synchronization error.

A. Conventional DCSK Receiver

Fig.1 shows the structure of conventional DCSK transceiver [3]. The discrete chaotic sequence \(s_i\) for one bit is represented as

\[
s_i = \begin{cases} x_i, & 0 < i \leq M \\ b_i x_{i-M}, & M < i \leq 2M \end{cases}
\]  

(2)

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where $x_i$ is a chaotic sequence, $b_l$ is $l$-th data bit, and $2M$ is the number of samples in one symbol. To detect the transmitted information signals, the received signal is multiplied by that received signal delayed by $M$. These products are added over $M$ for the detection process. Hence, the output of the correlator can be written as

$$S_l = \sum_{i=1}^{M} r_i r_{i+M}. \quad (3)$$

From Eq. (3), the received signal can be expressed as

$$r_i = s_i + \omega_i \quad (4)$$

where $\omega_i$ is a random noise, a stationary random process with zero mean and each one is statistically independent. Finally, the correlator output is

$$S_l = \sum_{i=1}^{M} (s_i + \omega_i)(s_{i+M} + \omega_{i+M}) \quad (5)$$

$$= \sum_{i=1}^{M} b_l x_i x_{i+M} + \sum_{i=1}^{M} x_i \omega_{i+M} + \omega_i x_{i+M} + \omega_i \omega_{i+M} \quad (6)$$

From this equation, the first term is desired signals and the second term is considered as noise components.

**B. Enhanced DCSK Receiver**

The operation of enhanced DCSK modulator and demodulator is illustrated in Fig. 2. As shown in this figure, it is almost same structure as conventional DCSK system except for the insertion of the guard time into the basis function at every other $\frac{M}{2}$. Thus, the enhanced DCSK requires only half detection period. Moreover, in lieu of reducing symbol period, the symbol energy is $\sqrt{2}$ times increased.

The different type of transmitted signal for proposed DCSK receiver is

$$s_i = \begin{cases} \sqrt{2}x_i, & 0 < i \leq \frac{M}{2} \\ \sqrt{2b_l}x_{i-M}, & M < i \leq \frac{3M}{2} \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

and the correlator output in enhanced DCSK receiver can be written as

$$S_l = \sum_{i=1}^{M} r_i r_{i+M}. \quad (8)$$

The length of silence period is flexible in terms of the application environments. One of the crucial design criteria for this can be the maximum channel delay.

**C. Consideration for the Synchronization Error**

The basis functions for both conventional DCSK and enhanced DCSK system can be defined from Eq. (2) and Eq. (7). In case of the symbol timing mismatch, the synchronization error can affect the basis functions. In conventional DCSK systems, the basis functions for $l$-th data bit can be represented as

$$g_{1l} = \begin{cases} b_{l-1} x_{(M+i+1)}, & -N < i \leq 0 \\ +x_{(i,l)}, & 0 < i \leq M \\ +x_{(i-M,l)}, & M < i \leq 2M - N \end{cases} \quad (9)$$

$$g_{2l} = \begin{cases} b_{l-1} x_{(M+i+1)}, & -N < i \leq 0 \\ +x_{(i,l)}, & 0 < i \leq M \\ -x_{(i-M,l)}, & M < i \leq 2M - N \end{cases} \quad (10)$$

where $b_{l-1}$ is $(l-1)$-th data bit$(\pm1)$, $x_{(i,l)}$ is the $i$-th chaotic sample consisting of $l$-th data bit and $N$ is the number of mismatched samples in symbol synchronization. Due to the mismatch of $N$ samples, a prior(or next) data bit and chaotic sequence in a neighboring bit can influence the orthogonality of basis functions, as shown in above equations. On the other hand, the basis functions for enhanced DCSK systems can be defined as

$$g_{1l} = \begin{cases} +\sqrt{2}x_{(i,l)}, & 0 < i \leq \frac{M}{2} - N \\ +\sqrt{2}x_{(i-M,l)}, & M < i \leq \frac{3M}{2} - N \end{cases} \quad (11)$$

$$g_{2l} = \begin{cases} +\sqrt{2}x_{(i,l)}, & 0 < i \leq \frac{M}{2} - N \\ -\sqrt{2}x_{(i-M,l)}, & M < i \leq \frac{3M}{2} - N \end{cases} \quad (12)$$

which mean that the basis functions for enhanced DCSK systems are independent of the neighboring data bit and chaotic...
sequences so that the orthogonality can hold even under the symbol timing mismatch. Fig.3 presents the synchronization error effecting the performance degradation by comparison between conventional DCSK scheme and enhanced DCSK approach. At first, we focus on the weakness of the DCSK scheme to the synchronization error. In Fig.3.(a), it is seen that the orthogonality of the basis functions can be destructed by chaotic sequences of the neighboring symbol due to the symbol synchronization error. In Fig.3.(b), as symbol duration is mismatched during differential detection, the ISI deteriorates the system performance. As shown in Fig.3.(c), the insertion of the silence interval between the reference period and information-carrying period not only maintain the orthogonality of the chaotic basis functions even in symbol synchronization error, but also reduce ISI.

However, the performance of enhanced DCSK is more sensitive to the symbol synchronization error even though the basis functions in Eq. (11), (12) satisfies the orthogonality of the basis functions. This phenomenon may be caused by the signal power loss in detection process. While the silence period between the reference and information interval makes free from the infection with chaotic sequences of the neighboring symbol, it has no signal power and renders the system performance more vulnerable to the synchronization error.

III. SIMULATION RESULTS

In our simulation, the bandpass filtered Gaussian random noise showing the same properties as conventional chaotic signal was adopted as the chaotic signal. The other parameters are $T_b = 400 \text{ ns} \ (2.5 \text{ Mbps})$, $200 \text{ ns} \ (5.0 \text{ Mbps})$ and $f_s = 16 \text{ GHz}$. The simulation environment is both Additive White Gaussian Noise (AWGN) channel and indoor residential LOS multipath channel proposed in IEEE 802.15.4a.

A. Conventional DCSK Receiver

In [2], the analytical BER performance of the DCSK system under the Gaussian assumption in AWGN channel was expressed as

$$\text{BER} = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{4 N_0}{E_b} + 4 M \left( \frac{N_0}{E_b} \right)^2} \right)^{-1}$$  (13)

where $M$ is a spreading gain equal to $0.5 f_s T_b$ ($f_s$ is sampling frequency and $T_b$ is time duration of one bit). This equation can not be adapted into any chaotic systems, especially requiring the lower spreading gain due to the characteristics of the chaotic signal. Fewer number of samples required for one bit would not sufficiently satisfy this Gaussian assumption. In other words, the Gaussian approximation would be justified for any $E_b/N_0$ if the spreading gain is sufficiently large. In our system, $M$ is used as 3200 for 2.5 Mbps data rate and as 1600 for 5.0 Mbps, enough sampling rate to keep this assumption. We can observe this result by comparison of the system performances in Fig.5 and Fig.7.
nization error. Every 10ns symbol time mismatch reduces the system performance by 0.3dB. Moreover, when we simulate DCSK scheme in multipath channel, those multipath effects cause the severe ISI between symbols and we can ascertain this phenomenon from the simulation results. Finally, we take into account the relationship between the data rate and the system performance shown in Fig.7. When the spreading gain is concerned, the decrease of the spreading gain (i.e., the increase of the data rate when the same sampling frequency is used) would lessen the bit error rate. We can also observe that the bit error rate is inversely proportional to the data rate under the Gaussian assumption.

B. Enhanced DCSK Receiver

In Fig.6, under the assumption of the perfect synchronization in AWGN channel, the BER performance of enhanced DCSK at the receiver is better than that of conventional DCSK by approximate 4dB at the target BER $10^{-3}$. In case of symbol timing mismatch, nearly 0.6dB performance leakage occurs in every 10ns symbol synchronization error. Although the orthogonality of the basis functions holds even in the symbol timing mismatch, different from the case of conventional DCSK receiver, the performance degradation of this scheme due to the timing mismatch is almost two times worse than that of the conventional method. This is because the power loss occurs when the receiver detects the transmitted signal under the synchronization error. In other words, enhanced DCSK receiver is more sensitive to the symbol synchronization error because of the signal power loss under the timing mismatch. In case of multipath channel, as we expected, enhanced DCSK receiver also shows 4dB better performance than does the DCSK receiver. The improvement in the system performance is from the effect of the insertion of the silence interval so that the period prevents from the performance degradation due to the interference from the other symbols and other undesired intervals for detection.

C. Performance Evaluation of the Enhanced DCSK Receiver

In general, when inserting the guard time for the signal transmission, we allocate the extra space for the silence time period so that there exists the capacity loss. However, in the chaotic communication, it is not necessary to assign this extra period, thanks to the property of the chaotic signals that chaotic signal does not change its bandwidth even in case of variation of the symbol period. Moreover, if the characteristics of the chaotic signals are sustained, we can obtain the better performance, proportional to the increase of the data rate. As we evaluated the performance of the DCSK receiver in terms of the data rate, the higher data rate enhanced DCSK system has, the better performance it shows. This simulation result is shown in Fig.7.

From the synchronization error’s point of view, we can compare the system performance of two DCSK modulations. From Fig.8, enhanced DCSK scheme is more susceptible to the synchronization error than conventional DCSK scheme. Even though the basis functions are well defined in enhanced DCSK systems against the synchronization error, the amount of aforementioned power loss in detection process is larger than that of pre-existing DCSK receiver. In the end, when we design the chaotic systems in which enhanced DCSK scheme is selected for transmission to improve the system performance,
the proposed system requires more accurate synchronization according to the stability of the system performance.

IV. CONCLUSIONS

In this paper, we propose enhanced DCSK scheme to increase the system performance both in AWGN channel and in multipath channel. About 4dB performance improvement is obtained in both channels. Furthermore, this efficient and powerful DCSK method keeps the orthogonality of the basis functions even in symbol timing mismatch condition. However, this enhanced DCSK receiver requires more stable and delicate synchronization accuracy in order to obtain better and more reliable system performance than that of conventional DCSK receiver. With respect to the data rate, the system performance of enhanced DCSK is better in higher data rate than in other cases if the characteristics of the chaotic signal for transmission are sustained.

V. ACKNOWLEDGMENT

This research was supported in part by SAIT (Samsung Advanced Institute of Technology)-ICU (Information and Communications Univeristy) joint project and the MIC(Ministry of Information and Communication), Korea, under the ITRC(Information Technology Research Center) support program supervised by the IITA(Institute of Information Technology Assessment).

REFERENCES


