Simultaneous Orthogonal Transmission for Direct Modulation Chirp Spread Spectrum Systems

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***Abstract*—A chirp spread spectrum (CSS) is classified into binary orthogonal keying (BOK) method that uses the orthogonal signals and direct modulation (DM) method that uses the antipodal signals. Since the DM method transmits the chirp waveform, the cross-correlation coefficient (CCC) should be considered as the BOK method. Thus, this paper proposes the simultaneous orthogonal transmission considering the CCC for the DM-CSS systems. The proposed scheme considers the multiple linear chirp and analyzes the CCC according to the separation bandwidth. The simulation results show that the proposed scheme can guarantee both antipodal property and orthogonality.**

***Index Terms*—internet of things, direct modulation, simultaneous transmission, cross-correlation coefficient, orthogonality**

I. Introduction

In order to sense environments and control numerous machines, various communication systems for wireless sensor networks (WSNs) are developed, and now evolving for the internet of things (IoT) [1]. Since the requirements for IoT are low-power, low-complexity, and long-distance communication, the long range (LoRa) technology has been developed [2]. In order to guarantee these requirements, the chirp spread spectrum (CSS) has been used for the physical layer for the IoT. The applications of the CSS have been already considered for various fields such as wireless communication [3], radar [4], underwater sensor networks [5], and wireless localization [6].

The CSS system is classified into binary orthogonal keying (BOK) and direct modulation (DM) [7]. In the BOK scheme, up-chirp and down-chirp are transmitted according to the data bit. Since these orthogonal signals are directly transmitted without any additional modulation, the complexity of the system is not high. However, since the two signals are not perfectly orthogonal, the BOK scheme should consider the cross-correlation coefficient (CCC) [8].

On the other hand, the DM scheme is similar to the pseudo noise-based direct-sequence spread-spectrum in that the chirp spreads the modulated signal. Thus, the DM scheme can transmit the antipodal symbols by up-chirp or down-chirp, obtaining the same bit error rate (BER) performance of binary phase shift keying (BPSK). However, since the DM scheme also transmits the chirp signals, the CCC must be analyzed for simultaneous transmission of a plurality of chirp. Therefore, we propose a simultaneous orthogonal transmission scheme for the DM-CSS system by analyzing the CCC. The proposed scheme considers the orthogonal CCC at specific separation bandwidth and allocates the bandwidth between the antipodal chirp signals.

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II. System Model

A. Conventional DM-CSS

Figure 1 shows the conventional DM-CSS system model. The up-chirp generated in the transmitter is expressed as [9] under the additive white Gaussian (AWGN) channel

$$c(t) = \left(\sqrt{2E_s/T_c}\right)\cos\left(2\pi f_c t + \pi\mu t^2\right), \qquad (1)$$

where E_s is the chirp energy, $-T_c/2 \leqslant t \leqslant T_c/2$, T_c is the chirp duration, f_c is the center frequency, $\mu = B/T_c$ is the chirp rate, and B is the total spreading bandwidth. Then, the received signal is

$$r(t) = s_i(t) + n(t), \qquad (2)$$

where $s_i(t) = -(-1)^i * c(t)$ is the antipodal chirp symbol according to the bit $i \in \{0, 1\}$, $n(t)$ is the AWGN. The receiver multiplies the received signal by the up-chirp and then decides the transmit bit based on the result of the correlator. Since, the

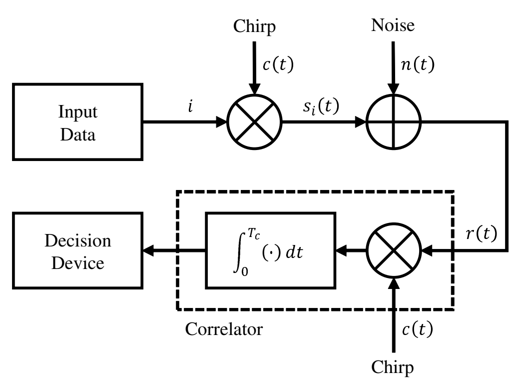

Fig. 1. Conventional DM-CSS system model [9]

chirp symbol has the antipodal property ($\rho = -1$) same as the BPSK, the BER performance is obtained as

$$P_e = Q\left(\sqrt{\frac{E_b(1-\rho)}{N_0}}\right) = Q\left(\sqrt{\frac{2E_b}{N_0}}\right), \qquad (3)$$

where $Q(x) \triangleq \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-t^2/2}dt$, E_b is the bit energy, N_0 is the noise power spectral density, and ρ is the CCC.

B. Simultaneous Transmission Method

In this paper, we assume the total number of chirps $K = \{2,4\}$, and the k-th chirp has the condition of $1 \leqslant k \leqslant K$. Then, the k-th single linear chirp (SLC) symbol according to the i-th bit can be expressed as

$$S_{i,k}(t) = A_i \cdot \cos\left(2\pi f_c t - (-1)^k \pi \mu_k t^2\right), \qquad (4)$$

where $A_i = -(-1)^i\left(\sqrt{2E_s/T_c}\right)$, $\mu_k = B_k/T_c$ and $B_k = B/\lfloor k/N \rfloor$ are the chirp rate and the bandwidth of the k-th SLC signal, respectively. Then, the CCC of the SLC according to a given total bandwidth B_Δ at the same bit is given [10]

$$\rho_\Delta^{\mathrm{SLC}} = \frac{1}{\sqrt{T_c B_\Delta}} C\left(\sqrt{T_c B_\Delta}\right), \qquad (5)$$

where $C(x) \triangleq \int_0^x \cos\left(\pi v^2/2\right)dv$ is the Fresnel's cosine integral [7]. On the other hand, if the chirp symbol is different the CCC of the SLC had the opposite direction $\left(-\rho_\Delta^{\mathrm{SLC}}\right)$. Since the CCC of the SLC cannot satisfy the orthogonality $\left(\rho_\Delta^{\mathrm{SLC}} \approx 0\right)$ even with the total bandwidth large enough, the BER performance may be deteriorated during the simultaneous transmission.

III. Simultaneous Orthogonal Transmission

For the simultaneous orthogonal transmission, we need to find the orthogonal separation bandwidth in a given total bandwidth. Previous studies have derived the CCC according to the separation bandwidth in the BOK method [8], [10], but we analyze the CCC of the DM method in this paper. Since the CCC is varied according to the total bandwidth and the separation bandwidth, the BER performance can be different even though the orthogonality has been guaranteed in the case of $K = 4$. In order to handle this issue, we assume the cognitive radio environments [11]. Thus, the system should allocate the primary separation bandwidth (PSB) for the primary chirp pairs ($k = \{1,2\}$) to guarantee both orthogonality and antipodal property. Then, the system allocates the secondary separation bandwidth (SSB) for the secondary chirp pairs ($k = \{3,4\}$) to guarantee orthogonality against the primary chirp pairs.

In order to guarantee the simultaneous orthogonal transmission, the degree of freedom such as the chirp sweeping direction and the bandwidth should be considered. Since the multiple linear chirp (MLC) can easily control the degree of freedom, we consider the MLC in this paper. The k-th MLC symbol of the front-chirp and the back-chirp according to the i-th bit can be expressed respectively as [10]

$$M_{i,k}^{\mathrm{fc}}(t) = A_i \cdot \cos\left(2\pi f_0 t + \pi \mu_k^{\mathrm{fc}}(t - T_r)^2\right), \qquad (6)$$

$$M_{i,k}^{\mathrm{bc}}(t) = A_i \cdot \cos\left(2\pi(f_0 + B_k)(t - T_r) + \pi \mu_k^{\mathrm{bc}}(t - T_r)^2\right), \qquad (7)$$

where $f_0 = f_c - \frac{B}{2}$ is the initial frequency, $0 \leqslant t \leqslant T_c$, $T_r = T_c/2$ is the half of the chirp duration, $\mu_k^{\mathrm{fc}} = B_k/T_c$ is the k-th front-chirp rate, and $\mu_k^{\mathrm{bc}} = (B - B_k)/T_c$ is the k-th back-chirp rate. Note that each bandwidth is determined by the CCC.

In order to find the orthogonal separation bandwidth for all the chirps, we need to analyze the CCC. The CCC of the MLC according to the separation bandwidth $B_\Delta^{\mathrm{SB}} \triangleq |B_k - B_j|$, where $1 \leqslant j \leqslant K$ $(j \neq k)$, at the same chirp symbol is [10]

$$\rho_\Delta^{\mathrm{MLC}} = \underbrace{\frac{1}{2\gamma_\Delta}C(\gamma_\Delta)}_{\text{Front-Chirp}} + \underbrace{\frac{1}{2\gamma_\Delta}\left\{\cos\left(\pi\frac{\gamma_\Delta}{2}\right)C(\gamma_\Delta) + \sin\left(\pi\frac{\gamma_\Delta}{2}\right)S(\gamma_\Delta)\right\}}_{\text{Back-Chirp}}, \qquad (8)$$

where $S(x) \triangleq \int_0^x \sin\left(\pi v^2/2\right)dv$ is the Fresnel's sine integral [7] and $\gamma_\Delta = \sqrt{T_c B_\Delta^{\mathrm{SB}}}$. Similarly, if the chirp symbol is different, the CCC of the MLC had the opposite direction $\left(-\rho_\Delta^{\mathrm{MLC}}\right)$. Here, the CCC $\rho_\Delta^{\mathrm{PSB}}$ of the PSB is calculated by the difference between the primary chirp pairs, i.e., $B_\Delta^{\mathrm{SB}} = |B_1 - B_2| = B_\Delta^{\mathrm{PSB}}$, and the CCC $\rho_\Delta^{\mathrm{SSB}}$ of the SSB is calculated by the difference between the selected primary chirp pair and one of the secondary chirp pairs, for example $B_\Delta^{\mathrm{SB}} = |B_1 - B_3| = B_\Delta^{\mathrm{SSB}}$. Finally, we can determined the bandwidth for the MLC as $B_1 = \frac{B}{2} - B_\Delta^{\mathrm{PSB}}$, $B_2 = \frac{B}{2} + B_\Delta^{\mathrm{PSB}}$, $B_3 = \frac{B}{2} - B_\Delta^{\mathrm{SSB}}$, and $B_4 = \frac{B}{2} + B_\Delta^{\mathrm{SSB}}$.

IV. Simulation Results

A. Simulation Environments

In order to evaluate the BER performance of the proposed scheme, the DM-CSS system model in Fig. 1 is considered. The chirp duration $T_c = 1$ μsec, the total bandwidth $B = 12$ MHz, the channel is the AWGN, and the total number of chirps $N = \{2,4\}$. Figure 2 shows the results of $\rho_\Delta^{\mathrm{PSB}}$ according to the PSB and $\rho_\Delta^{\mathrm{SSB}}$ according to the SSB when the PSB is selected. In the case of $K = 2$, in order to improve the BER performance of the MLC, the primary chirp pairs should select the PSB having the orthogonality $\left(\rho_\Delta^{\mathrm{PSB}} \approx 0\right)$. Therefore, we set $B_\Delta^{\mathrm{PSB}} = 3.206$ MHz. Similarly, in the case of $K = 4$, the secondary chirp pairs should select the SSB having the orthogonality $\left(\rho_\Delta^{\mathrm{SSB}} \approx 0\right)$ against the primary chirp

TABLE I
Simulation parameters

Parameter		Value
Chirp duration T_c		1 μsec
Chirp bandwidth B		12 MHz
Number of maximum chirps N		{2,4}
Total bandwidth for SLC	Primary	12 MHz
	Secondary	6 MHz
Separation bandwidth for MLC	Primary	3.206 MHz
	Secondary	9.323 MHz
Channel		AWGN

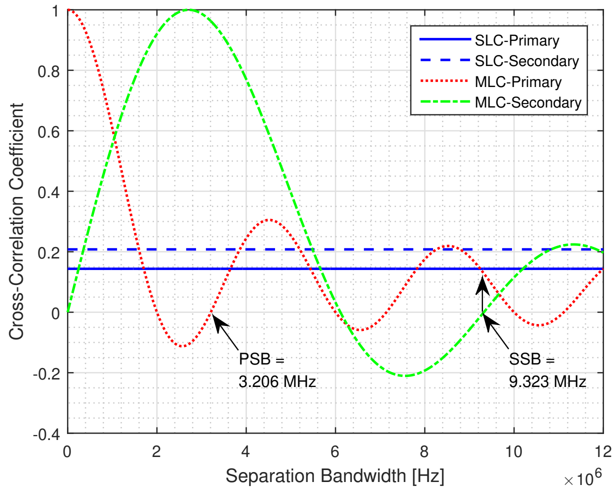

Fig. 2. CCC value according to the separation bandwidth

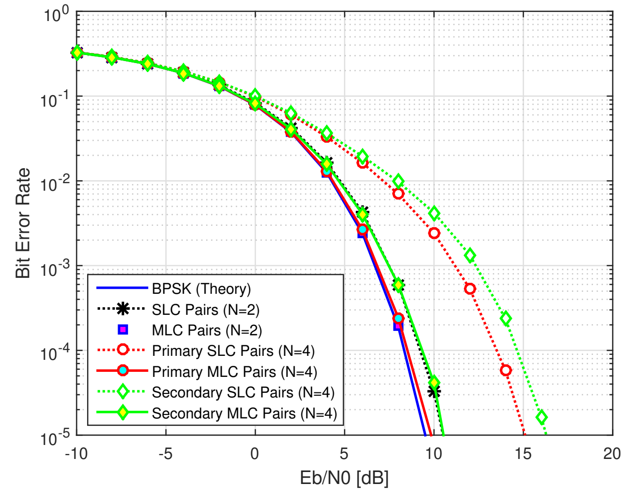

Fig. 3. BER performance according to E_b/N_0

pairs. Therefore, we set $B_{\Delta}^{\mathrm{SSB}} = 9.323$ MHz. However, since the secondary chirp pairs are affected by their CCC as drawn with the arrow in Fig. 2, they may not obtain the antipodal performance. Table 1 summarizes the simulation parameters. Note that the bandwidth of the SLC means the total bandwidth, while the bandwidth of the MLC is the separation bandwidth within a given total bandwidth.

B. BER Performance

Figure 3 shows the BER performance according to E_b/N_0. Simulation results are compared at BER of 10^{-3}. First, in the case of $K = 2$, since the SLC pairs cannot obtain the orthogonality, the BER performance of the SLC scheme is worse about 0.8 dB than the BPSK. On the other hand, since the MLC pairs can obtain the orthogonality, the BER performance of the proposed MLC scheme converges to the BPSK. Next, in the case of $K = 4$, the SLC scheme for the primary chirp pairs is worse about 4.3 dB than the BPSK, but the MLC scheme is close to the BPSK. For the secondary chirp pairs, the SLC scheme degrades by about 5.8 dB compared to the BPSK, and the MLC scheme degrades by about 0.8 dB because of their CCC. Consequently, since the secondary chirp pairs can perform the simultaneous orthogonal transmission, we can conclude that the proposed MLC scheme can expand the number of chirps within one chirp duration.

V. Conclusions

Since the conventional DM-CSS scheme transmits the antipodal signals, it can improve the BER performance compared to the BOK-CSS scheme. However, in order to simultaneously transmit a plurality of chirp signals, the DM method should also consider orthogonality between the chirps similar to the BOK method. In this paper, we analyze the CCC according to the PSB and the SSB to conduct simultaneous transmission in the DM-CSS system. Simulation results show that the proposed scheme can enable simultaneous orthogonal transmission within a given total bandwidth, which can expand the total number of chirps. Therefore, we can conclude that the proposed scheme has the advantages of both antipodal property and orthogonality. Moreover, the proposed method can be extended to the physical layer technology of the LoRa system as well as a multi-user environment and a multiple-input multiple-output system. In future works, we will analyze the BER performance in fading channels and measure the bandwidth efficiency when the priority is given according to the channel state.

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