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Multiple access interference and multipath interference analysis of orthogonal complementary code-based ultra-wideband systems over multipath channels

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SUMMARY

In order to alleviate multiple access interference and multipath interference of ultra-wideband (UWB) system, we propose the orthogonal complementary code (OCC)-based direct-sequence UWB system and offset-stacking (OS)-UWB system. OCC has perfect partial autocorrelation and cross-correlation characteristics. With the application of OCC in UWB system, we can obtain better performance in multiple access interference and multipath interference. The proposed OS-UWB structure can also achieve variable data rate transmission because of its innovative OS spreading technique. Theoretical analysis and simulation results show that the proposed UWB system can achieve excellent performance and outperform the unitary code-based direct-sequence UWB system. Copyright © 2013 John Wiley & Sons, Ltd.

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KEY WORDS: ultra-wideband (UWB); orthogonal complementary code (OCC); multiple access interference (MAI); multipath interference (MPI); offset-stacking spreading

1. INTRODUCTION

Ultra-wideband (UWB) technology [1] has gained considerable attentions since it was opened to civilian communication in 2002. Federal Communication Commission has regulated that UWB system operates within the frequency band from 3.1 GHz to 10.6 GHz with a power spectral density less than −41.3 dBm/MHz [2] and defined UWB technology with more flexibility that any technology can be recognized as UWB technology as long as it produces the signal with an absolute bandwidth exceeding 500 MHz or fractional bandwidth greater than 20%. The implementation for UWB signal is based on impulse radio [3], which mainly utilizes the baseband pulse. For its inherent characteristics, such as high data rate, relatively low system cost, low power spectrum density, and good resistance to severe multipath interference, etc, UWB becomes an excellent candidate for short-range high-speed wireless communications.

Typical low complexity direct-sequence (DS) spread spectrum system design over multipath fading channels can be seen in [4, 5], which aims to alleviate the influence of the multiple access interference (MAI) and multipath interference (MPI). In UWB system, MAI and MPI are also important factors that significantly affect the system performance over indoor and multi-user environments [6, 7]. And there are many literatures about the interference cancelation in UWB systems [8, 9]. Theoretical analysis of bit error rate (BER) for multiple access UWB system has been studied in [10–12]. Kotti *et al.* [13] highlighted the influence of

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spreading sequences on UWB system. Wu *et al.* and Cho *et al.* proposed ternary complementary code sets-based UWB system in [14, 15], which could alleviate the MPI and MAI. The application of multilevel complementary sets of sequences in UWB system was first investigated in [16]. Through the above studies of multiple access UWB systems, it is known that the selection of spreading codes plays an important role to improve the system performance.

Orthogonal complementary code (OCC) [17] set different from unitary codes, such as m sequence, Walsh code, and Gold sequence, is a kind of composite sequence set. OCC set, which consists of a group of element codes, has perfect correlation properties, that is, the side lobes of autocorrelation and cross-correlation functions are all zeros. The orthogonality of OCC set is achieved by the complementation between the corresponding element codes. The studies of OCC have been discussed in numerous literatures [18–20]. Chen *et al.* proposed OCC-based code division multiple access (CDMA) system to eliminate MAI and MPI, and employed offset-stacking (OS) modulation scheme to achieve variable data rates [21–25]. In this paper, we propose the OCC-based DS-UWB system and OS-UWB system, and present the corresponding performance analysis. Theoretical analysis and simulation results show that the two systems have better performance compared with unitary code-based UWB systems. The DS-UWB system architecture is simply compared with OS-UWB system. Moreover, the OS-UWB system can achieve variable data rate transmission because of its innovative OS spreading technique.

The rest of the paper is organized as follows. Section 2 introduces OCC and its characteristics. OCC-based DS-UWB and OS-UWB systems and the corresponding performance analysis are presented in Sections 3 and 4, respectively. Simulation results about the system performance of MAI are illustrated in Section 5. At last, we conclude this paper in Section 6.

2. CHARACTERISTICS OF ORTHOGONAL COMPLEMENTARY CODE

2.1. Orthogonal complementary code

We use the notation $\{K, M, N\}$ to characterize an orthogonal complementary spreading code set. In a given OCC set, the number of the flocks K is equal to the number of the element codes M. N is the element code length. Assume that we have two sequences $\boldsymbol{x} = \{x_1, x_2,\ldots, x_N\}$ and $\boldsymbol{y} = \{y_1, y_2,\ldots, y_N\}$. The partial autocorrelation function for sequence $\boldsymbol{x}$ can be defined as,

$$\rho(\boldsymbol{x}; l) = \begin{cases} \sum\limits_{j=1}^{N-l} x_j x_{j+l} & , \quad l = 0, 1, \cdots N-1 \\ \sum\limits_{j=1-l}^{N} x_j x_{j+l} & , \quad l = -1, \cdots, -N+1 \end{cases} \tag{1}$$

where l is the relative chip shift of the autocorrelation function.

Similarly, the partial cross-correlation function between $\boldsymbol{x}$ and $\boldsymbol{y}$ can be defined as follows,

$$\rho(\boldsymbol{x}, \boldsymbol{y}; l) = \begin{cases} \sum\limits_{j=1-l}^{N} x_j y_{j+l} & , \quad l = -1, \cdots, -N+1 \\ \sum\limits_{j=1}^{N-l} x_j y_{j+l} & , \quad l = 0, 1, \cdots N-1 \end{cases} \tag{2}$$

where l is the relative chip shift of the cross-correlation function.

$\{\boldsymbol{C}^1, \boldsymbol{C}^2, \ldots, \boldsymbol{C}^K\}$ is an OCC set. K, M, and N are three important parameters for the set. K is the set size, M is the flock size, and N is the element code length. $\mathbf{C}^k = \left\{\mathbf{c}_0^k, \mathbf{c}_1^k, \ldots, \mathbf{c}_i^k, \ldots, \mathbf{c}_{M-1}^k\right\}$ $(1 \le k \le K)$ is the kth flock in the code set, and $\mathbf{c}_i^k = \left\{c_{i0}^k, c_{i1}^k, \cdots, c_{ij}^k, \cdots, c_{iN-1}^k\right\}$ $(0 \le i \le M-1)$ is the ith element

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code in the *kth* flock. OCC has perfect correlation properties, and the correlation functions can be expressed as,

$$\begin{cases} \sum_{m=1}^{M} \rho\left(\mathbf{c}_m^i; l\right) = 0, \quad \textit{for} \;\; l \neq 0, \;\; i = 1, 2, \cdots, M \\ \sum_{m=1}^{M} \rho\left(\mathbf{c}_m^i, \mathbf{c}_m^j; l\right) = 0, \;\; \textit{for any} \;\; l, \;\; i \neq j, i, j = 1, 2, \cdots, M \end{cases} \tag{3}$$

2.2. Correlation properties

In this subsection, $\{A_0,A_1,A_2,A_3\}$ and $\{B_0,B_1,B_2,B_3\}$ are the two flocks of an OCC set and we take them as an example to illustrate the perfect partial correlation properties [18]. Figure 1 shows the autocorrelation of each element code of a flock and the sum of their autocorrelations. It can be seen that the autocorrelation of each element code is not so good, but the sum is a delta function $\delta(n)$. Similarly, owing to the complementation of element codes, the sum of the cross-correlations is zero for all l as depicted in Figure 2.

3. ORTHOGONAL COMPLEMENTARY CODE-BASED DS-UWB SYSTEM

In the following, we consider a multi-user UWB system with K users as shown in Figure 3. The uniformly distributed K users in the transmitter side can simultaneously send their signals to the receiver. We assume that all the users undergo the same multipath channel and the distance between the senders and receivers is within 10 meters, as the common indoor communication scenario.

For the OCC-based DS-UWB system, $\{\boldsymbol{C}^1,\boldsymbol{C}^2,\ldots,\boldsymbol{C}^K\}$ is an OCC set, which works on a flock per user basis, $\mathbf{C}^k = \left\{\mathbf{c}_0^k, \mathbf{c}_1^k, \ldots, \mathbf{c}_i^k, \ldots, \mathbf{c}_{M-1}^k\right\}$ $(1 \leq k \leq K)$ is the *kth* flock in the set, and $c_i^k = \left\{c_{i0}^k, c_{i1}^k, \cdots, c_{ij}^k, \cdots, c_{iN-1}^k\right\}(0 \leq i \leq M-1)$ is the *ith* element code in the *kth* flock. Each user is assigned one flock as DS code. As has been stated that one flock contains M element codes, however, M element codes of a user can not be transmitted together. A kind of transmission method must be adopted to distinguish M element codes. In this paper, we employ different transmission time to differentiate M element codes of a flock, i.e., we send the spreading

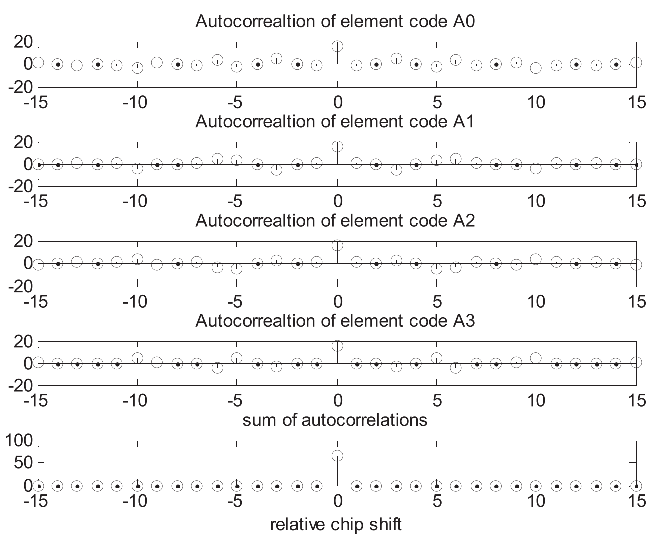

Figure 1. Individual autocorrelation and the sum of autocorrelations for orthogonal complementary code.

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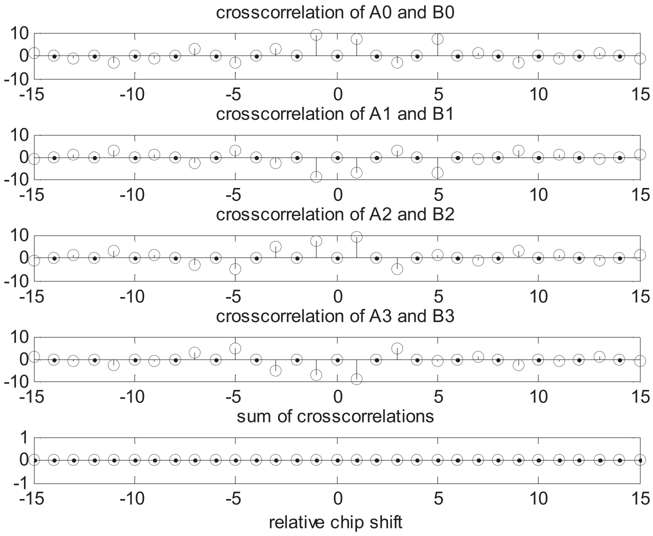

Figure 2. Individual cross-correlation and the sum of cross-correlations for orthogonal complementary code.

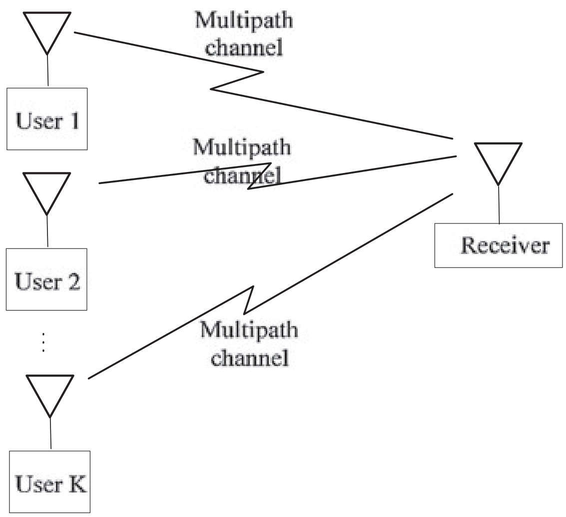

Figure 3. Multi-user ultra-wideband communication system.

sequences serially in time. Thus, the *kth* flock of the complementary code set is modified to $\mathbf{C}_{ZCZ}^k = \left\{ \mathbf{c}_0^k, \underbrace{0, \cdots 0,}_{\gamma+1} \mathbf{c}_1^k, \underbrace{0, \cdots, 0}_{\gamma+1}, \cdots, \mathbf{c}_{M-1}^k, \underbrace{0, \cdots, 0}_{\gamma+1} \right\}$ as the spreading sequence of the *kth* user. We assume that the maximum delay is τ and T_c is the chip duration. We have $\tau = \gamma T_c + \alpha$ and $\gamma = \lfloor \tau / T_c \rfloor$, where α is a random variable uniformly distributed over $[0, T_c]$. We insert zeros to distinguish M element codes. The number of zeros between $\mathbf{c}_i^k$ and $\mathbf{c}_{i+1}^k$ is relevant to the maximum delay. To guarantee complementation of element codes in an OCC set, the number of zeros between element codes must be $(\gamma + 1)$. If the maximum delay is more than a flock duration NT_c, the number of zeros is N.

3.1. System model and channel model

The transmitter diagram of the OCC-based DS-UWB system is shown in Figure 4. The expressions of the transmitted OCC-based DS-UWB signals are given by,

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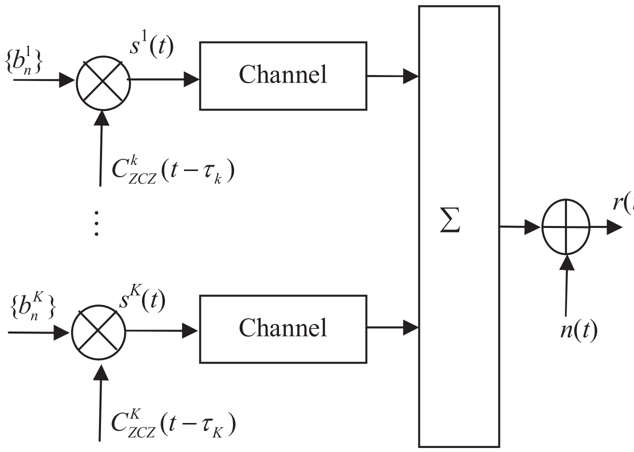

Figure 4. Transmitter diagram of orthogonal complementary code-based direct-sequence ultra-wideband system.

$$s^k(t) = \sqrt{\frac{E_b}{MN}} \sum_{n=-\infty}^{\infty} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} b_n^k c_{ij}^k w(t - nT_b - iT - jT_c) \tag{4}$$

where M and N are the flock size and the element code length of the OCC set, respectively. $\sqrt{E_b/MN}$ is the normalized amplitude factor and $w(t)$ is the pulse waveform. The pulse duration is T_w with $T_w \ll T_c$ and $T = (N+\gamma+1)\cdot T_c$, $T_b = MT$ is the duration of a bit symbol. $d_n^k \in \{0, 1\}$ is the *nth* information bit transmitted by the *kth* user, and $b_n^k = 2d_n^k - 1$ is the modulated signal with bipolar pulse amplitude modulation (BPAM). $C_{ZCZ}^k(t)$ in Figure 4 is given as $C_{ZCZ}^k(t) = \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} c_{ij}^k w(t - iT - jT_c)$, and c_{ij}^k denotes the *jth* chip of the *ith* element code of the *kth* user, which also takes the value from $\{\pm 1\}$. τ_k is the asynchronous delay of the *kth* user uniformly distributed over $[0, NT_c]$.

The channel impulse response of the *kth* user can be modeled simply as,

$$h^k(t) = \sum_{l=0}^{L-1} \alpha_{k,l}\delta\left(t - \tau_{k,l}\right) \tag{5}$$

where L is the number of the resolvable multipath components. For the *kth* user, $\alpha_{k,l}$ represents the *lth* path gain. $\tau_{k,l}$ is the *lth* delay, it can be described by the delay of the cluster and the delay of the ray relative to the cluster.

3.2. System performance analysis

The received signal is given as,

$$r(t) = \sum_{k=1}^{K} \sum_{l=0}^{L-1} \alpha_{k,l} s^k\left(t - \tau_k - \tau_{k,l}\right) + n(t) \tag{6}$$

where τ_k is the asynchronous delay of the *kth* user, $n(t)$ is additive white Gaussian noise (AWGN) with double sided power spectral density $N_0/2$.

We assume that the first user is the desired user, and the data bit b_0^1 is transmitted. Here, the perfect synchronization is also assumed. To improve the link performance, SRake receiver is employed in this paper. The template signal used in the $l'th$ branch of the SRake receiver is given as $v_{l'}(t) = \alpha_{1,l'} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} c_{ij}^1 w\left(t - iT - jT_c - \tau_{1,l'}\right)$. The statistic decision output of the $l'th$ correlator is given by,

$$Z_{l'} = \int_0^{T_b} r(t) v_{l'}(t) dt = S + I + M + N \tag{7}$$

where $S = \alpha_{l'}^2 b_0^1 \sqrt{E_b MN}$ denotes the desired signal part, $N = \int_0^{T_b} n(t) \alpha_{l'} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} c_{ij}^1 w(t - iT - jT_c - \tau_{l'}) dt$ is the noise term. I and M are the MAI and MPI terms, respectively, which relate to the relative delay. If $|\tau_l - \tau_{l'}| < NT_c$ and $\tau_l - \tau_{l'} < 0$, that is, the relative path delay of the desired user is less than the duration of a flock, and the delay of the $l'th$ path is greater than the delay of the lth path, term I can be written as,

$$I = \sum_{l=0, l \neq l'}^{L-1} \sqrt{\frac{E_b}{NM}} \alpha_{l'} \alpha_l b_0^1 \left[\sum_{i=0}^{M-1} \rho\left(c_i^1, c_i^1; \gamma_{ll'}\right) \cdot F_w(\alpha_{ll'}) + \sum_{i=0}^{M-1} \rho\left(c_i^1, c_i^1; \gamma_{ll'} + 1\right) \cdot \hat{F}_w(\alpha_{ll'}) \right]. \tag{8}$$

If $|\tau_l - \tau_{l'}| < NT_c$ and $\tau_l - \tau_{l'} > 0$, that is, the delay of the $l'th$ path is less than the delay of the lth path, term I can be expressed as,

$$I = \sum_{l=0, l \neq l'}^{L-1} \sqrt{\frac{E_b}{NM}} \alpha_{l'} \alpha_l b_0^1 \left[\sum_{i=0}^{M-1} \rho\left(c_i^1, c_i^1; -\gamma_{ll'}\right) \cdot R_w(\alpha_{ll'}) + \sum_{i=0}^{M-1} \rho\left(c_i^1, c_i^1; -(\gamma_{ll'} + 1)\right) \cdot \hat{R}_w(\alpha_{ll'}) \right]. \tag{9}$$

Similarly, if $|\tau_k + \tau_l - \tau_{l'}| < NT_c$ and $\tau_k + \tau_l - \tau_{l'} < 0$, that is, the relative path delay between the desired user and the kth user is less than the duration of a flock, and the delay of the $l'th$ path of the desired user is greater than the delay of the lth path of the kth user, M can be expressed as,

$$M = \sum_{k=2}^{K} \sum_{l=0}^{L-1} \sqrt{\frac{E_b}{NM}} \alpha_{l'} \alpha_l b_0^k \left[\sum_{i=0}^{M-1} \rho\left(c_i^k, c_i^1; \gamma_{kll'}\right) \cdot F_w(\alpha_{kll'}) + \sum_{i=0}^{M-1} \rho\left(c_i^k, c_i^1; \gamma_{kll'} + 1\right) \cdot \hat{F}_w(\alpha_{kll'}) \right]. \tag{10}$$

If $|\tau_k + \tau_l - \tau_{l'}| < NT_c$ and $\tau_k + \tau_l - \tau_{l'} > 0$, that is, the delay of the $l'th$ path of the desired user is less than the delay of the lth path of the kth user, M can be obtained as,

$$M = \sum_{k=2}^{K} \sum_{l=0}^{L-1} \sqrt{\frac{E_b}{NM}} \alpha_{l'} \alpha_l b_0^k \left[\sum_{i=0}^{M-1} \rho\left(c_i^k, c_i^1; -\gamma_{kll'}\right) R_w(\alpha_{kll'}) + \sum_{i=0}^{M-1} \rho\left(c_i^k, c_i^1; -(\gamma_{kll'} + 1)\right) \cdot \hat{R}_w(\alpha_{kll'}) \right]. \tag{11}$$

Here, we introduce the following ancillary. The relative multipath delay $|\tau_l - \tau_{l'}|$ and $|\tau_k + \tau_l - \tau_{l'}|$ can be expressed as,

$$|\tau_l - \tau_{l'}| = \gamma_{ll'} T_c + \alpha_{ll'} \tag{12}$$

$$|\tau_k + \tau_l - \tau_{l'}| = \gamma_{kll'} T_c + \alpha_{kll'} \tag{13}$$

where $\gamma_{ll'} = \lfloor |\tau_l - \tau_{l'}| / T_c \rfloor$, $\gamma_{kll'} = \lfloor |\tau_k + \tau_l - \tau_{l'}| / T_c \rfloor$. $\alpha_{ll'}$ and $\alpha_{kll'}$ are the random variables uniformly distributed over [0, T_c].

The template signal used in the $\acute{l}$th branch of the SRake receiver may lags or be priors to the other paths. Thus, the autocorrelation functions of $w(t)$ are defined as,

$$\hat{F}_w(s) = \begin{cases} \int_0^{T_c - s} w(t)w(t+s)dt & 0 \le s \le T_c \\ 0 & elsewhere \end{cases} \tag{14}$$

$$\hat{F}_w(s) = \begin{cases} \int_{T_c - s}^{T_c} w(t)w(t - T_c + s)dt & 0 \le s \le T_c \\ 0 & elsewhere \end{cases} \tag{15}$$

$$R_w(s) = \begin{cases} \int_0^{s} w(t)w(t + T_c - s)dt & 0 \le s \le T_c \\ 0 & elsewhere \end{cases} \tag{16}$$

$$\hat{R}_w(s) = \begin{cases} \int_s^{T_c} w(t)w(t - s)dt & 0 \le s \le T_c \\ 0 & elsewhere \end{cases}. \tag{17}$$

According to the characteristics of OCC, we have $I = 0$ and $M = 0$, that is, the partial MPI and MAI can be eliminated for this OCC-based DS-UWB system. Hence, both the multipath interference and the multiple access interference can be alleviated because of the perfect correlation properties of the OCC.

4. ORTHOGONAL COMPLEMENTARY CODE-BASED OFFSET-STACKING ULTRA-WIDEBAND SYSTEM

The OS spreading technique is first introduced by Chen in [17]. The most significant characteristic is that the bit stream is no longer aligned in time one bit after another. Instead, a new bit will be sent right after n-chip delay relative to the previous bit. Thus, the consecutive bits are stacked with n relative offset chips, where n may take any integer from 1 to N (the element code length). With this method, variable data rate can be achieved by shifting the offset chips between the neighboring bits. To improve the link performance, SRake receiver can also be considered in the receiver. However, because of the employment of OS spreading scheme in the UWB system, SRake receiver can be released for some cases. If the maximum channel delay is greater than the offset chips between the neighboring bits, the multipath components of the desired bit will be overlapped by the multipath components of the other interference bits. Thus, SRake receiver is no longer suitable in this case. But if the maximum channel delay is smaller than the relative offset chips, with SRake receiver, the useful multipath components can be separated from the interference bits because of the perfect correlation properties of the OCC. We assume that the maximum channel delay is less than the flock duration in the following analysis.

We propose a kind of parallel OS-UWB transmitter structure as depicted in Figure 5. Each user's data bits are first transformed from serial to parallel with P branches. For each branch, the same information bit is duplicated by M sub-branches. Each sub-branch is modulated by one pulse train. The expression of the OS OCC-UWB signal for the *kth* user is given by,

$$s^k(t) = \sum_{j=0}^{P-1} \sqrt{\frac{E_b}{MN}} b^k(j) \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} c_{mn}^k w_m(t - nT_c - jT) \tag{18}$$

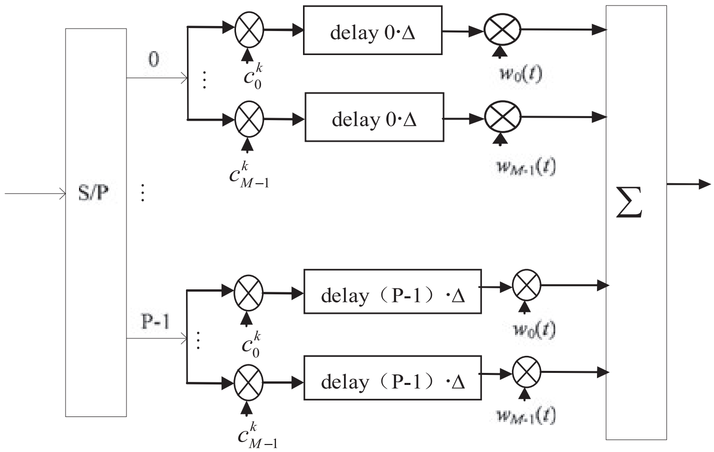

Figure 5. Transmitter diagram of orthogonal complementary code-based offset-stacking ultra-wideband system.

where $w_m(t)$ is the unit energy pulse chosen from the orthogonal pulse set. $b^k(j)$ is the *jth* bit transmitted by the *kth* user. $T = \Delta T_c$, and Δ is the relative offset chips between the neighboring bits.

For a synchronous UWB system with K users, the received signal is expressed by,

$$r(t) = \sum_{k=1}^{K}\sum_{j=0}^{P-1}\sum_{l=0}^{L-1}\alpha_l\sqrt{\frac{E_b}{MN}}b^k(j)\sum_{m=0}^{M-1}\sum_{n=0}^{N-1}c_{mn}^k w_m(t-nT_c-lT_c-jT)+n(t). \tag{19}$$

We also assume that the first user is the desired user, and the bit $b^1(j')$ is transmitted. To realize diversity reception, SRake receiver is also considered. The statistical decision output of the *l'th* correlator is calculated as,

$$\begin{aligned} Z_1^{j'} &= MN\alpha_{l'}^2\sqrt{\frac{E_b}{MN}}b^1(j') + \sum_{l=0,l\neq l'}^{L-1}\alpha_{l'}\alpha_l\sqrt{\frac{E_b}{MN}}b^1(j')\sum_{m=0}^{M-1}\rho\left(c_m^1, c_m^1; (l-l')\right) \\ &+ \sum_{j=0,j\neq j'}^{P-1}\sum_{l=0}^{L-1}\alpha_{l'}\alpha_l\sqrt{\frac{E_b}{MN}}b^1(j)\sum_{m=0}^{M-1}\rho\left(c_m^1, c_m^1; (j-j')\Delta+(l-l')\right) \\ &+ \sum_{k=2}^{K}\sum_{j=0}^{P-1}\sum_{l=0}^{L-1}\alpha_{l'}\alpha_l\sqrt{\frac{E_b}{MN}}b^k(j)\sum_{m=0}^{M-1}\rho\left(c_m^1, c_m^k; (j-j')\Delta+(l-l')\right)+n \end{aligned}. \tag{20}$$

The first term in the right side of (20) is the useful signal component. The third term denotes the interference part caused by the other bits of the first user. The second and the fourth terms are the multipath interference and multiple access interference, respectively. The second term is zero considering $l \neq l'$. We set $\Delta > \lfloor \tau_{\max}/T_c \rfloor + 1$ to obtain $|(j-j')\Delta| > |l-l'|$, where $\tau_{\max}$ is the maximum channel delay. According to the characteristics of OCC, the total multipath interference and the multiple access interference can be zero. The signal-to-noise ratio (SNR) per bit for the decision variable of bit $b^1(j')$ is written as,

$$\gamma = \sum_{l'=0}^{L-1}\gamma_{l'} = \frac{\sum_{l'=0}^{L-1}|\alpha_{l'}|^2}{N_0/2E_b} = \frac{2E_b\sum_{l'=0}^{L-1}|\alpha_{l'}|^2}{N_0}. \tag{21}$$

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Hence, the average system BER can be obtained by,

$$P_e = \int_0^{\infty} Q\left(\sqrt{2\gamma}\right) f_{\gamma}(\gamma) d\gamma \tag{22}$$

where $f_\gamma(\gamma)$ is the PDF of SNR. Although an exact closed-form expression for the PDF of a sum of independent lognormal random variables does not exist, such a sum can be approximated by another lognormal random variable. The approximation can be obtained by Wilkinson's method as [26, 27].

Let $\gamma_{l'} = e^{\varepsilon + 2y_{l'}}$, where $\varepsilon = \ln\left(\frac{2E_b}{N_0}\right)$ and $y_{l'} \sim N\left(m_{y_{l'}}, \sigma^2_{y_{l'}}\right)$ are normal random variables. Let $\gamma = e^z$ with $z \sim N(m_z, \sigma_z^2)$, the two parameters m_z and σ_z^2 can be obtained by matching the first two moments of γ. These two parameters are given as,

$$m_z = 2\ln u_1 - \frac{1}{2}\ln u_2 \tag{23}$$

$$\sigma_z^2 = \ln u_2 - 2\ln u_1 \tag{24}$$

with $u_1 = \sum_{l'=0}^{L-1} e^{\left(\varepsilon + 2m_{y_{l'}} + 2\sigma^2_{y_{l'}}\right)}$, $u_2 = \sum_{l'=0}^{L-1} e^{2\left(\varepsilon + 2m_{y_{l'}} + 2\sigma^2_{y_{l'}}\right)} + 2\sum_{i,j=0}^{L-1} e^{2\left(\varepsilon + m_{y_i} + m_{y_j} + \sigma^2_{y_i} + \sigma^2_{y_j}\right)}$.

The approximated PDF of γ is given as,

$$f_\gamma(\gamma) = \frac{1}{\gamma\sqrt{2\pi\sigma_z^2}} \exp\left(-\frac{(\ln\gamma - m_z)^2}{2\sigma_z^2}\right). \tag{25}$$

5. SIMULATION RESULTS

In this section, we provide the simulation results about the OCC-based DS-UWB and OS-UWB systems over IEEE 802.15.3a CM1 channel [2]. The transmitted pulse can be modeled as the second

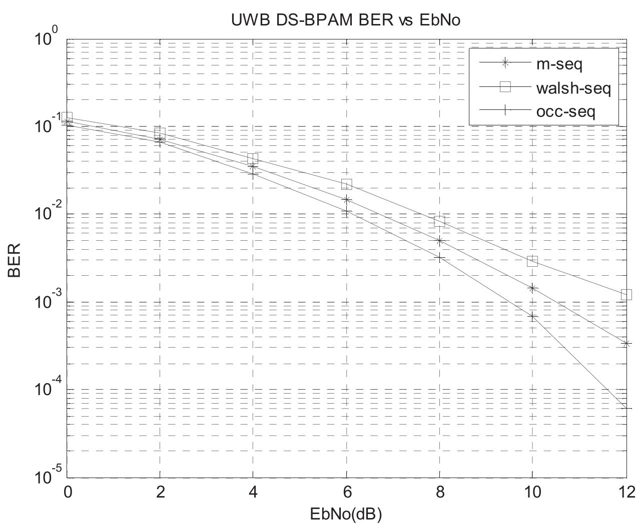

Figure 6. Bit error rate performance of the orthogonal complementary code-based direct-sequence ultra-wideband system over CM1 channel (single user).

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order Gaussian monocycle with $w(t) = \left[1 - 4\pi\left(\frac{t}{\tau_m}\right)^2\right] \exp\left[-2\pi\left(\frac{t}{\tau_m}\right)^2\right]$ in DS-UWB system, where $\tau_m = 0.2$ ns, $T_w = 0.5$ ns. We use modified Hermite polynomial functions as the orthogonal pulses in OS-UWB system.

Figures 6 and 7 show the BER performance of the OCC-based DS-UWB system over CM1 channel. In single user case, it is shown that the OCC-based system outperforms the system based on m sequence and Walsh code, especially at high SNRs. The OCC-based system can obtain about 3.0 dB gains when BER is 10^{-3} compared to Walsh code-based system. We can also see from Figure 7 that the UWB systems with m sequence and Walsh code suffer more severe multiple access interference than OCC-based system due to the fact that the orthogonality among either the m sequence or Walsh code is destroyed in the transmission. From these simulation results, it is easy to know that the alleviation of the multiple access interference and multipath interference closely relates to the selection of the spreading sequence.

The BER performance of OCC-based OS-UWB system over IEEE 802.15.3a CM1 channel is shown in Figure 8. We assume that the maximum channel delay is $10T_c$. In single user case, it is

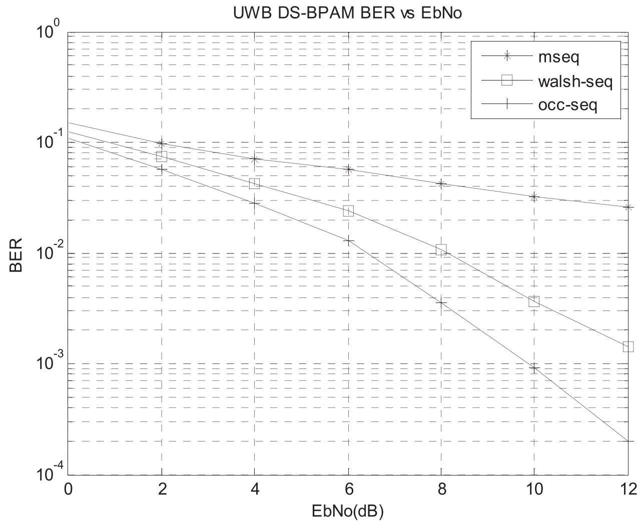

Figure 7. Bit error rate performance of the orthogonal complementary code-based direct-sequence ultra-wideband system over CM1 channel (4 users).

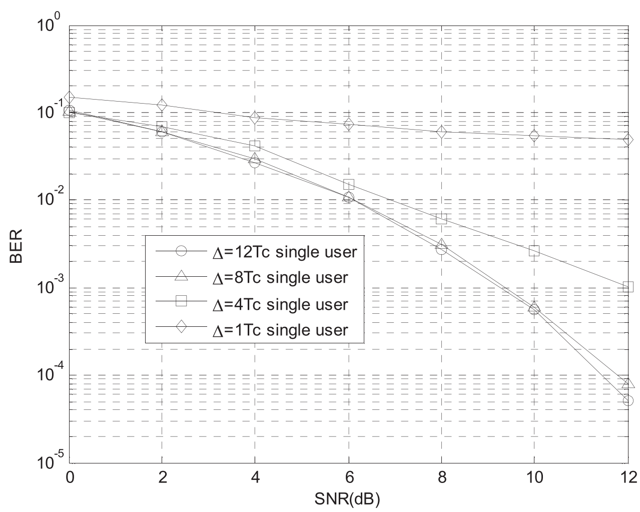

Figure 8. Average bit error rate of offset-stacking ultra-wideband system for different offset chips (Δ) between neighboring bits over CM1 channel.

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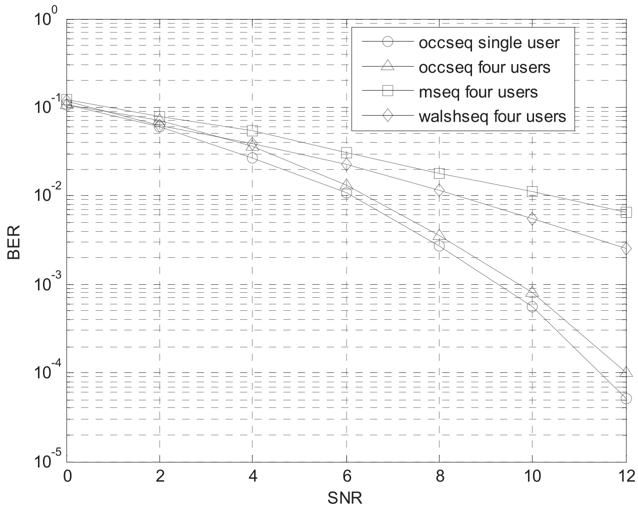

Figure 9. Average bit error rate of orthogonal complementary code-based offset-stacking ultra-wideband system over CM1 channel (4 users).

seen that the system performance is influenced by the offset chips (Δ). The BER descends much with the increase of the offset chips Δ because the multipath components of the desired bit will be overlapped by the multipath components of the other interference bits when Δ is less than the maximum channel delay. As seen from Figure 9, the OCC-based OS-UWB system can achieve about 2.0 dB and 4.0 dB gains when BER is about 10^{-2} compared with Walsh code and *m* sequence-based systems, respectively. The UWB systems with *m* sequence or Walsh code suffer more severe interference due to the fact that the orthogonality among these sequences is destroyed by the multipath interference. The system performance of the OCC-based four user OS-UWB system grades little compared with the single user system. It is found that the mitigation of the multiple access interference and multipath interference to the system performance depends much on the spreading sequence.

6. CONCLUSIONS

In this paper, we propose OCC-based DS-UWB and OS-UWB systems with bipolar pulse amplitude modulation. The system structure of DS-UWB system is simpler, but the OS-UWB system can flexibly support variable data rate because of the application of OS spreading modulation scheme. The BER performance analysis of the two systems over multipath channels is presented. Theoretical analysis and simulation results show that the MAI as well as MPI can be alleviated over multipath channels because of the perfect correlation properties of OCC in the two systems. The OCC-based UWB system can achieve better performance compared with the unitary code-based UWB systems.

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