Design and Analysis on U-VLC-CC-CDMA Systems

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Abstract. Visible light communication (VLC) has dual functions of communication and lighting, and is widely used in the next generation wireless communication field. A suitable multiple access method is needed in the multi-user scenario of visible light communication to eliminate interference. This paper designs a VLC code division multiple access (VLC-CDMA) using complementary codes (CCs). CCs have ideal autocorrelation and cross-correlation properties, which can be used to distinguish different users. The issues on periodicity and correlation of CCs in VLC-CDMA systems are discussed as preliminaries. The transmitter uses LEDs of different wavelengths to separate different sub-codes in the CCs. The compensation circuit is used to synthesize white light and realize equal gain combination of the received signals. The receiver uses a filter with different central wavelength to separate signals transmitted by different sub-codes and convert them into electrical signals. B/U and U/B modules at transmitter and receiver are designed to complete the conversion between unipolar signals and bipolar signals. The anti-interference performance and a theoretical analysis on BER are conducted to verify the effectiveness. In addition, we compare the performance of VLC-CDMA systems using CC, Walsh sequences and Gold sequences, which shows that VLC-CDMA system using CCs can eliminate multi-user and multi-path interference.

Keywords: Visible light communication · CDMA · Complementary code

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1 Introduction

Visible light communication (VLC) adopts indoor basic lighting facilities, which has dual functions of lighting and communication [1–3]. Visible light communication has many advantages, but we also need to pay attention to the challenges. In multi-user scenarios, such as shopping malls and supermarkets, a suitable multiple access method is needed to meet the requirements of multi-user communication [4,5].

Code division multiple access (CDMA) technology has the function of satisfying the simultaneous access of multiple users to the network [6–8]. Therefore, we use CDMA technologies to achieve multiple access in VLC, which is named as VLC-CDMA. However, indoor optical signal transmission belongs to scattering link, and multipath transmission will cause multipath interference to visible light CDMA system [9]. Therefore, it is necessary to adopt appropriate methods to eliminate or suppress multipath and multiuser interferences. VLC-CDMA technology inherits the advantages of CDMA technology in conventional CDMA wireless communications [10].

The performance of a communication system using CDMA technology is greatly affected by correlations of signature codes. The resistance to multipath interference for the system is determined by the autocorrelation characteristics of the signature codes. The cross-correlation characteristics of the two signature codes reflect the multiple access interference (MAI) between two users in the system [11]. Therefore, the expectation of the correlation characteristics for signature codes in the communication system using CDMA technology is: 1) Ideal autocorrelation characteristics, that is, the correlation function of each signature code has only one impulse function when zero shift, and function values are all zero in other shifts; 2) The ideal cross-correlation characteristic, that is, the function value of any two signature codes is zero at any shifts.

In VLC systems, the signal transmitted by the LED is required to be positive and real, so a polarity conversion module needs to be added before the signal is loaded into the LED [12]. A common unipolar processing method is to add DC offset at the transmitter and remove it at the receiver [13]. In this paper, the method of code conversion is used to realize the polarity conversion of signals. Unipolar processing is performed on spread signal, which can guarantee the signal entering LED is positive and real. Based on previous researches [14,15], the design method of transmitter and receiver of U-VLC-CC-CDMA system is proposed in this paper.

The above discussion requires us to propose a suitable VLC-CDMA system design. The main contributions of this paper are as follows.

1) In this work, we introduce unipolar VLC-CDMA using complementary codes, which is named as U-VLC-CC-CDMA system.
2) We design the transmitters and receivers for the U-VLC-CC-CDMA systems. The transmitter uses LEDs of different wavelengths to separate different subcodes in the CCs. The compensation circuit is used to synthesize white light and realize equal gain combination of the received signals. The receiver uses

a filter with different central wavelength to distinguish signals transmitted by different sub-codes and convert them into electrical signals. B/U and U/B modules at transmitter and receiver are designed to complete the conversion between unipolar signals and bipolar signals.

3) We analyze the anti-interference capability and BER of the designed U-VLC-CC-CDMA system. The performance of U-VLC-CDMA system with CCs, Walsh sequences and Gold sequences are compared in simulation results.

2 System Model

In this section, we analyze the preliminaries of CCs, which are used as the signature codes in the designed U-VLC-CC-CDMA system. Then, we introduce a VLC-CDMA system model, which includes transmitter, and receiver.

2.1 Preliminaries of CCs

Theorem 1. *The two sequences are* $\mathbf{a} = [a_1, a_2, \cdots, a_N]$ *and* $\mathbf{b} = [b_1, b_2, \cdots, b_N]$*, the length of the two sequences are both* N*, the aperiodic correlation function of two sequences can be expressed as [10]:*

$$\phi(\mathbf{a}, \mathbf{b}; \delta) = \begin{cases} \sum_{i=1}^{N-\delta} a_i b_{i+\delta}, & 0 \leq \delta \leq N-1 \\ \sum_{i=1}^{N+\delta} a_{i-\delta} b_i, & 1-N \leq \delta < 0 \end{cases}. \tag{1}$$

Signature codes with aperiodic ideal correlation characteristics are more suitable for practical communication systems, which can eliminate multipath interference and multiple access interference in CDMA communication systems. Therefore, the aperiodic ideal correlation characteristics of signature codes play an important role in the performance of communication systems using CDMA technology [16].

Denote a family of complementary codes as $\mathcal{C}(K, M, N)$, where K is the number of complementary codes, M represents the number of sub-codes in each complementary code, and N is the length of sub-codes. The matrix $\mathbf{C}^{(k)}$ is used to represent the kth complementary code in a family of complementary codes, $k \in \{1, 2, \cdots, K\}$, namely:

$$\mathbf{C}^{(k)} = \begin{bmatrix} \mathbf{c}_1^{(k)} \\ \mathbf{c}_2^{(k)} \\ \vdots \\ \mathbf{c}_M^{(k)} \end{bmatrix} = \begin{bmatrix} c_{1,1}^{(k)} & c_{1,2}^{(k)} & \cdots & c_{1,N}^{(k)} \\ c_{2,1}^{(k)} & c_{2,2}^{(k)} & \cdots & c_{2,N}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ c_{M,1}^{(k)} & c_{M,2}^{(k)} & \cdots & c_{M,N}^{(k)} \end{bmatrix}, \tag{2}$$

where $\mathbf{c}_m^{(k)}$ represents the mth sub-code in the complementary code, $m \in \{1, 2, \cdots, M\}$.

The autocorrelation function of the complementary code can be calculated through this group of sub-codes, thereby reflecting its ideal autocorrelation characteristics. Since the signal transmission in the actual communication system needs to adopt aperiodic form, it is necessary to express the correlation function $\rho(\mathbf{C}^{(k_1)}, \mathbf{C}^{(k_2)}; \delta)$ of the complementary codes $\mathbf{C}^{(k_1)}$ and $\mathbf{C}^{(k_2)}$ as the sum of the aperiodic correlation functions of M sub-codes in the two complementary codes, which is shown in (3), $k_1, k_2 \in \{1, 2, \cdots, K\}$. Many research works have proved that when the number of sub-codes M in a family of complementary codes $\mathcal{C}(K, M, N)$ is not less than the number of supported users K by the system, the complementary codes can be guaranteed to achieve aperiodic ideal correlation properties [10], namely :

$$\rho(\mathbf{C}^{(k_1)}, \mathbf{C}^{(k_2)}; \delta) = \sum_{m=1}^{M} \phi(\mathbf{c}_m^{(k_1)}, \mathbf{c}_m^{(k_2)}; \delta) = \begin{cases} MN, & \delta = 0, k_1 = k_2 \\ 0, & \text{elsewhere} \end{cases}. \tag{3}$$

Compared with the signature codes used in traditional wireless communication, the biggest feature of complementary codes is its multiple sub-codes structure. In an actual communication system, the information of each user will be transmitted using multiple sub-codes of a complementary code, and its ideal autocorrelation characteristics can be achieved through multiple sub-codes. The signature codes of multiple users also need to use corresponding multiple sub-codes for cross-correlation calculation, so as to achieve ideal cross-correlation characteristics.

2.2 Transmitter

The transmitters and modulation are LEDs and Binary Phase Shift Keying (BPSK) in the VLC-CDMA system. The system transmitter model is shown in Fig. 1. $b^{(k)}$ is the signal of the kth user after BPSK. Each user data is copied to M data streams, and $b_m^{(k)}$ is the mth data stream of the kth user, where $m \in \{1, 2, \cdots, M\}$, $k \in \{1, 2, \cdots, K\}$. A set of complementary codes $\mathcal{C}(K, M, N)$ are used as the signature codes for K users in the system. Assume that $\mathbf{C}^{(k)} = \{\mathbf{c}_m^{(k)}\}_{m=1}^{M}$, $k \in \{1, 2, \cdots, K\}$ is the signature code for user k, shown as (2).

Assume that there are K users in the system, and a CC is assigned for each user. M data streams of a user are multiplied by M sub-codes of a CC. Since LEDs in the VLC system use IM/DD modulation, there is no phase information. Therefore, there is no negative physical quantity, we need to do a polarization process of the signal before it is modulated to LED, as shown in Fig. 1. The B/U module converts bipolar signals into unipolar signals to adapt to the physical characteristics of the VLC system. Regarding the specific processing process of the B/U module, we will introduce it in the next section.

LEDs are used to transmit spread signal. $F_m, m \in \{1, 2, \cdots, M\}$ are the optical filter gain for the receiving end. $\gamma_m, m \in \{1, 2, \cdots, M\}$ are the PD response sensitivity. Therefore, we add compensator circuits for LEDs with the gains of $1/(F_m \times \gamma_m), m \in \{1, 2, \cdots, M\}$, which is power allocation of a single LED to include multi-chip LED. According to this, equal gain combination can be obtained at the receiver, which can achieve the ideal correlation characteristics of CCs.

A separate LED is assigned to each data stream for a user, which can guarantee LEDs work in the linear regions [6]. Different sub-codes for one user adopt LED with different wavelength, which can eliminate mutual interference between subcodes of the same user. The specific process is explained as follows.

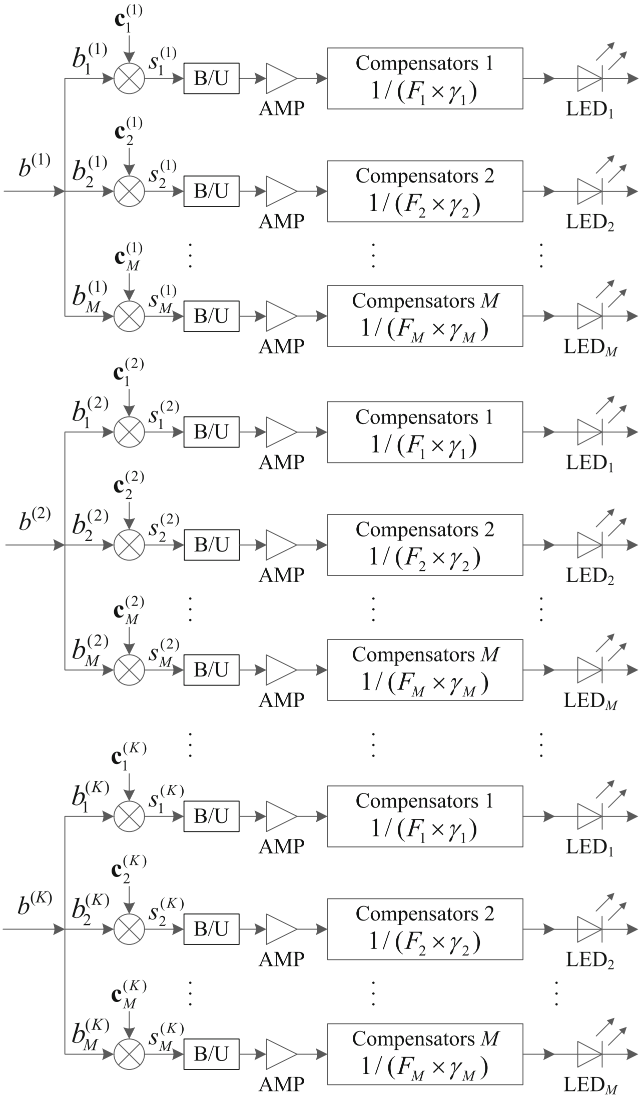

Fig. 1. Transmitters structure of the VLC-CC-CDMA system.

The spreading waveform of the mth sub-code for user k is

$$C_m^{(k)}(t) = \sum_{n=1}^{N} c_{m,n}^{(k)} q(t - nT_c + T_c), \tag{4}$$

where $m \in \{1, 2, \cdots, M\}$, $n \in \{1, 2, \cdots, N\}$, $k \in \{1, 2, \cdots, K\}$, which are the same definitions in the rest of the paper. T_c is duration of one chip, $q(t)$ is chip pulse waveform with $q(t)$ being a rectangular pulse for simplicity, denoted as

$$q(t) = \begin{cases} \frac{1}{\sqrt{MNT_c}}, & 0 \leq t < T_c \\ 0, & \end{cases}. \tag{5}$$

2.3 Receiver

We take the single user receiver structure as an example to analyze the system reception process, as shown in Fig. 2. The signal at the receiving end is the sum of all different LED signals. Bandpass filters are required to separate each data stream of different sub-code spread spectrum, which need to select filters with the same structure and different central wavelengths.

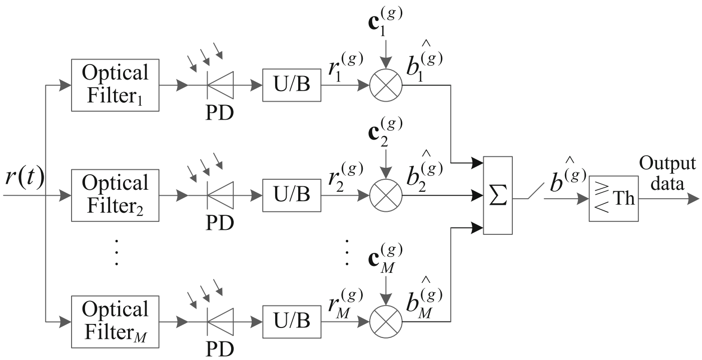

Fig. 2. Receivers structure of the VLC-CC-CDMA system with a single user.

The peak wavelengths of LEDs are: 400 nm, 450 nm, 507 nm, 545 nm, 600 nm, 650.2 nm, 700 nm and 750 nm, respectively. The FWHM are: 10 nm, 25 nm, 30 nm, 36 nm, 15 nm, 17.3 nm, 30 nm and 30 nm, respectively. Therefore, the bandpass filters at the receiver are assumed to be the model of Asahi Company [17], as shown in Table 1.

PDs are used to convert optical signals to electrical signals. For the chip of OSRAM Company, it is assumed that a silicon-based PIN photodetector BPX61 is used. On one hand, this chip is used in the experimental design literature, on the other hand, the photoelectric conversion efficiency value 0.53 A/W used in many literatures is consistent with this chip [1,7,18], and the chip has a high

Table 1. The chips and the parameters of the optical filters selected by receivers.

Optical filters	Center wavelength (nm)	FWHM (nm)	Transmission F (%)
ZBPA400	400±2	10±2	61.2262
ZBPB005	450±5	40±10	67.1512
ZBPB0026	500±5	40±10	67.5536
ZBPB050	550±5	40±10	74.0802
ZBPB090	600±5	20±10	78.6086
ZBPB124	650±5	40±10	77.2932
ZBPB146	700±5	60±10	84.1494
ZBPA750	750±3	12±3	87.0652

photoelectric conversion efficiency (maximum 0.62 A/W) and a large viewing angle (110°). The response sensitivity values of different wavelengths can be obtained by the spectral sensitivity curve of the PDs, shown as,

$$\begin{aligned}\gamma(\lambda) = &-2031 - 2423\cos(0.003251\lambda) + 2449\sin(0.003251\lambda)\\ &+ 47.08\cos(0.006502\lambda) + 1866\sin(0.006502\lambda)\\ &+ 468.9\cos(0.009735\lambda) + 449\sin(0.009753\lambda)\\ &+ 112.7\cos(0.013004\lambda) - 5.614\sin(0.013004\lambda).\end{aligned} \tag{6}$$

For chips from Hamamatsu [6,19] can be assumed. Using the same method as BPX61, we can also obtain the corresponding sensitivity expression according to the response sensitivity curve given in the chip data. Therefore, we can obtain the different response sensitivity values at each wavelength. The unipolar signals received by the system are converted into bipolar signals through the U/B module, and then the bipolar signals obtained are added together and decided by an appropriate threshold to recover the transmitted data.

3 System Design and Analysis

In this section, we show the specific code conversion method through B/U and U/B for VLC-CC-CDMA system. Meanwhile, we give theoretical analysis on the ways to eliminate interference and derive BER.

3.1 U-VLC-CC-CDMA System

The main principle of polarity conversion of the U-VLC-CC-CDMA system is to remap the spread spectrum signal. If the spread signal "s" is positive, then map the signal to "$s0$, if the spread signal is negative, then map the signal to "$0|s|$, so as to ensure that the signal entering the LED is positive and real, which meets the requirements of the VLC system. Corresponding processes are performed at the receiver to restore it to a bipolar signal. The ideal correlation characteristics of the complementary code are used to restore the signal. This parallel method needs to use two times different wavelengths of LEDs, half of the LEDs are used to transmit the first one of each pair of data, and the other half of the LEDs are used to transmit the second one of each pair of data. The detailed processing procedure is as follows.

Transmitter: Assuming that the system uses the modulation method of BPSK, the modulated signal is bipolar after multiplying by the signature code. A code conversion process is required to meet the requirements of the VLC system, that is, the B/U module in Fig. 1. The signal becomes unipolar through the B/U module. The signal passing through the B/U module is represented by the symbol $s_{m\mathrm{PU}}^{(k)}$, then the parallel signals $s_{m\mathrm{PU1}}^{(k)}(t)$ and $s_{m\mathrm{PU2}}^{(k)}(t)$ can be expressed as (7) and (8). Figure 3 shows a schematic diagram of a unipolar transformation.

$$s_{m\mathrm{PU1}}^{(k)}(t) = \begin{cases} s_m^{(k)}(t), & s_m^{(k)}(t) > 0 \\ 0, & s_m^{(k)}(t) < 0 \end{cases}. \tag{7}$$

$$s_{m\mathrm{PU2}}^{(k)}(t) = \begin{cases} 0, & s_m^{(k)}(t) > 0 \\ -s_m^{(k)}(t), & s_m^{(k)}(t) < 0 \end{cases}. \tag{8}$$

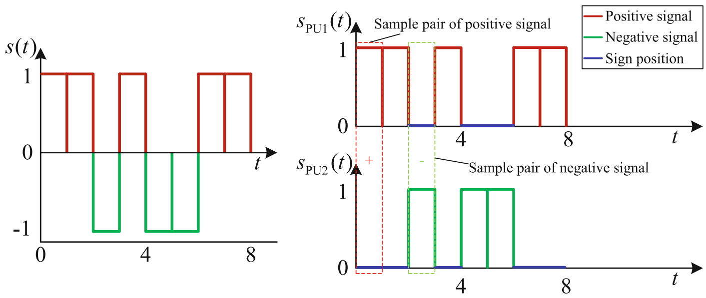

Fig. 3. The unipolar signals are changed from bipolar signals by parallel paired transform.

Therefore, the two parallel signals after the unipolar transformation are:

$$\begin{cases} s^{(k1)}(t) = \sum_{m=1}^{M} s_{m\mathrm{PU1}}^{(k)}(t) S_{m1}(\lambda) \frac{1}{F_{m1}\gamma_{m1}} \\ s^{(k2)}(t) = \sum_{m=1}^{M} s_{m\mathrm{PU2}}^{(k)}(t) S_{m2}(\lambda) \frac{1}{F_{m2}\gamma_{m2}} \end{cases}, \tag{9}$$

where $S_{m1}(\lambda)$ is the spectral expression of the first LED in the mth channel, and $S_{m2}(\lambda)$ is the spectral expression of the second LED in the mth channel [21]. $\lambda = ct$, c is the speed of light, F_{m1} and γ_{m1} are the gain of the first filter and photodetector in the mth path, F_{m2} and γ_{m2} are the gain of second filter and photodetector in the mth path.

Receiver: through optical filters and photodetectors and adding noise to the signal, the mth signal of the gth user is transmitted by two channels from the transmitter, $r_{m\mathrm{PU1}}^{(g)}$ and $r_{m\mathrm{PU2}}^{(g)}$ are shown as

$$\begin{cases} r_{m\mathrm{PU1}}^{(g)}(t) = \sum_{k=1}^{K} h_m^{(k1)}(t) s_{m\mathrm{PU1}}^{(k)}(t-\tau_k) + n_{m1}(t) \\ r_{m\mathrm{PU2}}^{(g)}(t) = \sum_{k=1}^{K} h_m^{(k2)}(t) s_{m\mathrm{PU2}}^{(k)}(t-\tau_k) + n_{m2}(t) \end{cases}, \tag{10}$$

where τ_k is the delay of the mth data stream on user k.

It is necessary to use the inverse transformation of the code to convert the unipolar signal into a bipolar signal before despread, which is shown as the U/B module in Fig. 2. The paired detection signal recovery method of the U-VLC-CC-CDMA system is: subtract the second bit from the first bit of each pair of data, and the result obtained is the original signal. The processed signal $r_m^{(g)}$, shown as

$$\begin{aligned} r_m^{(g)}(t) &= r_{m\mathrm{PU1}}^{(g)}(t) - r_{m\mathrm{PU2}}^{(g)}(t) \\ &= \sum_{k=1}^{K} h_m^{(k1)}(t) s_{m\mathrm{PU1}}^{(k)}(t-\tau_k) + n_{m1}(t) - \left[\sum_{k=1}^{K} h_m^{(k2)}(t) s_{m\mathrm{PU2}}^{(k)}(t-\tau_k) + n_{m2}(t) \right]. \end{aligned} \tag{11}$$

Generally, it is assumed that the channel state information passed by the two LEDs in each channel are the same, that is, $h_m^{(k1)}(t) = h_m^{(k2)}(t) = h_m^{(k)}(t)$ [21–23]. Therefore, (11) can be expressed as:

$$r_m^{(g)}(t) = \sum_{k=1}^{K} h_m^{(k)}(t) s_m^{(k)}(t-\tau_k) + n_{m1}(t) - n_{m2}(t). \tag{12}$$

At the end, M data streams of one user are added together and decided by an appropriate threshold to recover the transmitted data. The detail analysis is given as follows.

Step 1: The despread process of the jth data of the mth data stream for the gth user.

The electrical signals are converted from optical signals by PDs. The CC for user k is used to despread data streams of the use g. Assume that the receiver and signals of the user g can achieve ideal synchronization, and the despread results is

$$\begin{aligned} \widehat{b}_m^{(g)}(j) &= \int_0^{NT_c} r_m^{(g)}(t + jT_b + \tau_g) C_m^{(g)}(t) \mathrm{d}t \\ &= \sqrt{P_t} h_m^{(g)} b^{(g)}(j) + I_m^{(g)} + v_m, \end{aligned} \tag{13}$$

where τ_g is the delay of the mth data stream of user g. The simplification of (13) includes three terms. The first item shows the despread results of the jth data on the mth data stream of user g. The last term is the noise, which is still an additive Gaussian process. $I_m^{(g)}$ expresses the interference for the mth data stream of the user g from other users as

$$I_m^{(g)} = \sum_{k=1,k\neq g}^{K} \sqrt{P_t} h_m^{(k)} \left\{ \alpha_m^{(k)} b_m^{(k)}(j) + \beta_m^{(k)} b_m^{(k)} \left[j + \mathrm{sgn}(\delta_\mathrm{k}) \right] \right\}, \tag{14}$$

where sgn(x) is "1" when $x \geq 0$, and is "-1" when $x < 0$. δ_k is the relative delay of the mth data stream between the kth and the gth users, $\delta_k = (\tau_g - \tau_k)/T_c$. The values of $\alpha_m^{(k)}$ and $\beta_m^{(k)}$ are determined as

$$\begin{cases} \delta_k > 0 : \alpha_m^{(k)} = \phi(\mathbf{c}_m^{(g)}, \mathbf{c}_m^{(k)}; \delta_k), \quad \beta_m^{(k)} = \phi(\mathbf{c}_m^{(k)}, \mathbf{c}_m^{(g)}, N - \delta_k) \\ \delta_k < 0 : \alpha_m^{(k)} = \phi(\mathbf{c}_m^{(k)}, \mathbf{c}_m^{(g)}; -\delta_k), \quad \beta_m^{(k)} = \phi(\mathbf{c}_m^{(g)}, \mathbf{c}_m^{(k)}, N + \delta_k) \\ \delta_k = 0 : \alpha_m^{(k)} = \phi(\mathbf{c}_m^{(g)}, \mathbf{c}_m^{(k)}; 0), \quad \beta_m^{(k)} = 0 \end{cases}, \tag{15}$$

where $\phi(\mathbf{a}, \mathbf{b}; \delta)$ is the non-periodic correlation function of $\mathbf{a}$ and $\mathbf{b}$, which is defined as (1).

Step 2: The combination of the M data streams. The M data streams of the gth user can achieve equal gain combination, which is shown as

$$\widehat{b}^{(g)}(j) = \sum_{m=1}^{M} \widehat{b}_m^{(g)}(j) = \sqrt{P_t} \sum_{m=1}^{M} h_m^{(g)} b_m^{(g)}(j) + I^{(g)} + V, \tag{16}$$

where $I^{(g)}$ and V are the interference and noise terms, respectively. Based on this result, we present theoretical analysis on anti-interference characteristics and BER in Sect. 3.2.

Step 3: Data recovered with an appropriate threshold.

In this step, we usually set the appropriate threshold as 0 in simulations, so we can obtain jth data on the mth data stream and recover the M data streams for user g.

3.2 Theoretical Analysis on Elimination of Interference and BER

Assume that the system in the case of flat fading, that is, $h_1^{(g)} = h_2^{(g)} = \cdots = h_M^{(g)} = h^{(g)}$. From (13), the final decision threshold that can detect the ith data of user g is

$$\widehat{b}^{(g)}(i) = M \sqrt{P_t} h^{(g)} b^{(g)}(i) + I_\mathrm{U}^{(g)} + V_\mathrm{U}. \tag{17}$$

Analysis on Elimination of Interference: Let us analyze the interference term $I_U^{(g)}$ in (17). We have

$$\begin{aligned} I_\mathrm{U}^{(g)} &= \sum_{m=1}^{M} I_m^{(g)} \\ &= \sqrt{P_t} \sum_{m=1}^{M} \sum_{k=1,k\neq g}^{K} h_m^{(k)} \left\{ \alpha_m^{(k)} b_m^{(k)}(j) + \beta_m^{(k)} b_m^{(k)} \left[j + \mathrm{sgn}(\delta_\mathrm{k}) \right] \right\} \\ &= \sqrt{P_t} \sum_{k=1,k\neq g}^{K} \left\{ b^{(k)}(j) \varPsi_1 + b^{(k)} \left[j + \mathrm{sgn}(\delta_\mathrm{k}) \right] \Psi_2 \right\}, \end{aligned} \tag{18}$$

where $\varPsi_1=\sum_{m=1}^{M} h_m^{(k)}\alpha_m^{(k)}$ and $\varPsi_2=\sum_{m=1}^{M} h_m^{(k)}\beta_m^{(k)}$.

On the basis of VLC channel models in [21], we can see that the channels are flat and $h_1^{(k)}=h_2^{(k)}=\cdots=h_M^{(k)}$. Moreover, we have added compensator circuits in the transmitters. Therefore, the VLC-CC-CDMA system can realize an equal gain combining of all sub-codes through the correlation functions. Substitute (15) into $\varPsi_1$ and $\varPsi_2$. Comparing $\varPsi_1$ and $\varPsi_2$ with the correlation characteristics of CCs defined by (3), we can see that the $\varPsi_1=0$ and $\varPsi_2=0$. Thus, MAI can be eliminated completely using the above system assumption.

Derivation of BER: The third term in (13) is the noise term, $V=\sum_{m=1}^{M} v_m$. v_m is a statistical independent Gaussian random variable, whose sum is also a Gaussian random variable. Based on the previous analysis in [21], the expectation of noise is zero and its variance is

$$\mathrm{var}[V] = \sigma_{\mathrm{thermal}}^2 + \sigma_{\mathrm{shot}}^2, \tag{19}$$

where $\sigma_{\mathrm{thermal}}^2$ and σ_{shot}^2 are shown in (20) and (21), respectively.

$$\sigma_{\mathrm{thermal}}^2 = \frac{8\pi k_B \mathcal{T_K} \eta A_{\mathrm{PD}} I_2 B^2}{\mathcal{G}} + \frac{16\pi^2 k_B \mathcal{T_K} \varepsilon \eta^2 A_{\mathrm{PD}}^2 I_3 B^3}{\mathfrak{g}}, \tag{20}$$

where k_B is Boltzmann constant, $\mathcal{T_K}$ is absolute temperature, η is fixed capacitance per unit area of the PD, A_{PD} is the area of the PD, and I_2 is noise bandwidth factor. B is noise bandwidth equal to the value of data rate (R_b). $\mathcal{G}$ is open-loop voltage gain. ε is the channel noise factor of field effect transistor (FET), I_3 is noise bandwidth factor, and $\mathfrak{g}$ is the transconductance of the FET.

The variance of shot noise is usually $2e\gamma P_r B + 2eI_{bg}I_2B$, where e is the electron charge, γ is the sensitivity of the PD, P_r is received optical power, and I_{bg} is background current [1,7]. However, in the proposed VLC-CC-CDMA system, the receivers have not only the sensitivity gains of PDs, but also the gains of the optical filters. We have added compensators with the gain of $1/F_m\gamma_m$ at the transmitters to compensate the gains of optical filters and PDs at the receiver. Therefore, we can not consider the gains of optical filters and PDs, and use P_r directly instead of γP_r. The variance of shot noise of each data stream can be modified as

$$\sigma_{\mathrm{shot}}^2 = 2eP_rB + 2eI_{bg}I_2B. \tag{21}$$

Let $P_t = \frac{E_b}{MNT_c}$. E_b is bit energy, and the system SINR can be obtained as

$$\mathrm{SINR} = \frac{E_b}{\mathrm{var}[I^{(g)}] + \mathrm{var}[V]}. \tag{22}$$

As OOK modulation is used in the system, the bit error rate is

$$\mathrm{BER_{OOK}} = Q\left(\sqrt{\frac{SINR}{2}}\right), \tag{23}$$

where, $Q(x)$ is expressed as

$$Q(x) = \frac{1}{2\pi}\int_{x}^{\infty} e^{\frac{-t^2}{2}dt}. \tag{24}$$

4 Simulation Details and Results

In this section, we show the simulation results of U-VLC-CDMA systems. We present and compare BER performances of U-VLC-CDMA systems with CC, Walsh sequences and Gold sequences.

4.1 Simulation Setup

The room model is assumed as $5 \times 5 \times 3$ m^3 and empty to eliminate intereference from other light sources. At the transmitter, four different LEDs can compose white light to achieve the duel function of lighting and communication. Optical signal is transmitted through indoor scattering link, and the channel model is discussed in [21]. The receiver is 2.15 m away from the transmitter and installed on a desktop with the height of 0.85 m. The data length is 10^6, the noise parameters are shown in Table 2.

We use $\mathcal{C}(4, 8, 4)$ as signature codes in the VLC-CC-CDMA system, i.e., the length of sub-codes (N) is 8, the number of sub-codes (M) is 4, and the number of users supported by each complementary code (K) is 4. We choose Walsh sequences and Gold sequences for a comparative experiment, which is widely used in CDMA systems. Specifically, the length of Walsh sequences (N) is 32, expressed as Walsh32. The length of Gold sequences (N) is 31, expressed as Gold31. Therefore, it is guaranteed that the processing gains MN of the three codes are the same. During system simulation, four user codes of Walsh32 and Gold31 are taken to ensure that they support the same number of users as the system using complementary codes.

According to the correlation function expression of (1), the correlation characteristics of $\mathcal{C}(4, 8, 4)$, Walsh32 and Gold31 used in the simulation are given. Figure 4 and Fig. 5 show their autocorrelation and cross-correlation function properties.

From Figs. 4 and 5, complementary codes have ideal autocorrelation and cross-correlation properties. The autocorrelation function of Gold31 is ideal and can resist multi-path interference. The cross-correlation function of Walsh32 has ideal characteristics and can resist multi-user interference. However, the even-periodic characteristics of signal propagation cannot be guaranteed, and a non-periodic scenario in general is usually assumed. Then, as shown in Figs. 4 and 5, neither Walsh sequences nor Gold sequences have ideal autocorrelation and cross-correlation properties at the same time. Therefore, the system using complementary codes has better resistance to multi-path and multi-user interference.

Table 2. Simulation Parameters.

Optical filters	Center wavelength (nm)
LEDs power	0.88 W
Semi-angle at half power ($\varphi_{1/2}$)	60°
Radiation angle (φ)	30°
FOV at a receiver	60°
Photodetector responsivity (γ_1, γ_2, γ_3, γ_4)	0.42, 0.25, 0.16, 0.35 A/W
Transmission of optical filter (F_1, F_2, F_3, F_4)	78.8%, 73.1%, 68.1,% 80.4%
Background light current (I_{bg})	5100 μA
Noise bandwidth factor 2 (I_2)	0.562
Noise bandwidth factor 3 (I_3)	0.0868
Detector area (A_{PD})	1 cm^2
Absolute temperature ($\mathcal{T_K}$)	295 K
Boltzmann constant (k_B)	1.23×10^{-23} J/K
FET channel noise factor (ε)	1.5
Open-loop voltage gain ($\mathcal{G}$)	10
FET transconductance ($\mathfrak{g}$)	30 mS
Fixed capacitance (η)	112 pF/cm^2
Electron charge (e)	1.6×10^{-19} C

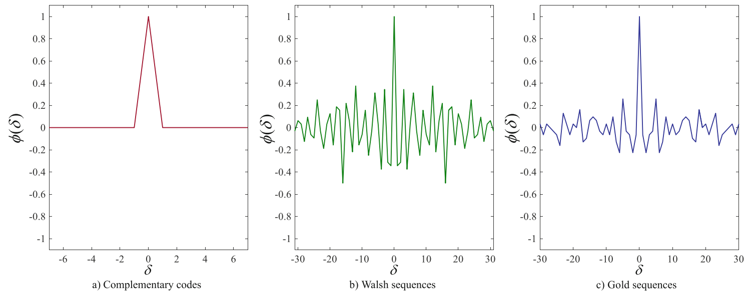

Fig. 4. Auto-correlation properties of $\mathcal{C}(4,8,4)$, Walsh32 and Gold31.

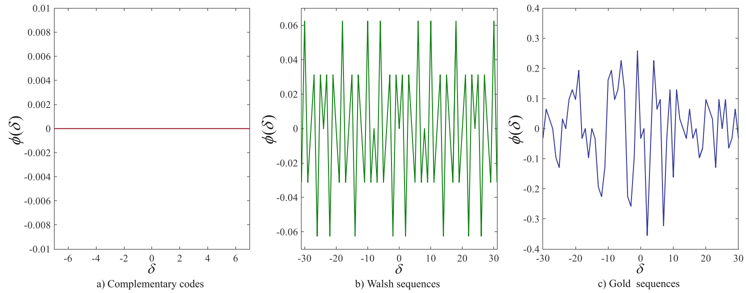

Fig. 5. Cross-correlation properties of $\mathcal{C}(4,8,4)$, Walsh32 and Gold31.

4.2 Simulation Results

In the simulation results of U-VLC-CC-CDMA system, the chip rate is 240 Mcps, and the data rates of systems using complementary codes, Walsh sequences and Gold sequences are 30 Mbps, 7.5 Mbps and 7.74 Mbps, respectively. The system adopts the parallel polarity conversion scheme, and the receiver adopts the method of subtracting the second bit from the first bit in each pair of values. The simulation results are shown in Figs. 6 and 7.

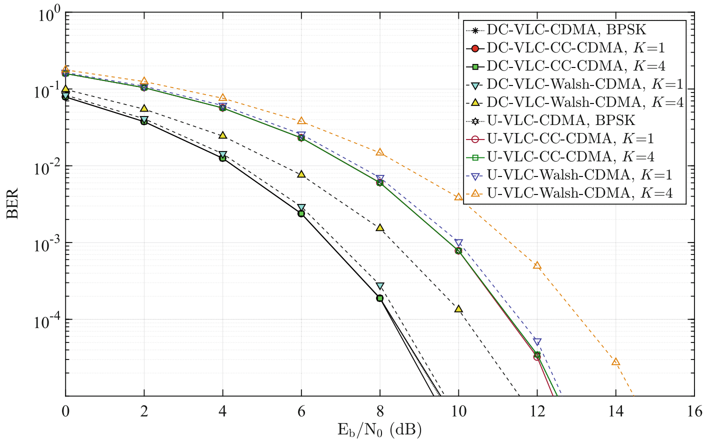

Fig. 6. BER performance of U-VLC-CDMA and DC-VLC-CDMA systems with CCs and Walsh sequences.

It can be seen from Figs. 6 and 7 that the system performance becomes better with the increase of the SNR. For obvious reasons, system performance can be improved by increasing the SNR. When the number of users K=1, the BER curves using complementary codes, Walsh sequences and Gold sequences are all coincident with the theoretical curves, which because there is no multi-user interference in the system. With the increase of the number of users, when K = 4, only the system BER using the complementary codes still basically coincides with the theoretical curves. The reason is that only the complementary codes can achieve the ideal autocorrelation and cross-correlation characteristics, which makes the system free from multi-path and multi-user interferences. However, the BER performance of Walsh sequences and Gold sequences will be deteriorated, which because the correlation characteristics of the two signature codes are not ideal, and they cannot resist multi-path and multi-user interferences. Since the chip rate is assumed to be the same in the simulation, the communication rate using the complementary codes is four times that of using the Walsh sequences and the Gold sequences.

In addition, in the U-VLC-CC-CDMA system, the parallel mode avoids the phenomenon of signal aliasing, therefore, the receiver can restore the original

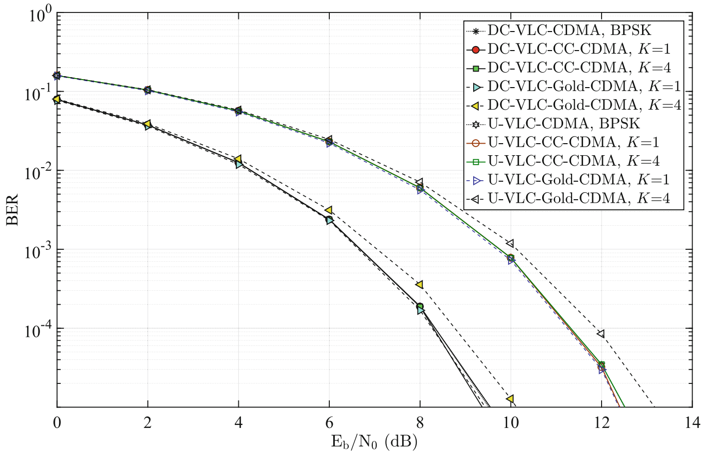

Fig. 7. BER performance of U-VLC-CDMA and DC-VLC-CDMA systems with CCs and Gold sequences.

signal. However, since the receiver adopts the method of subtracting two signals, the noise is doubled, and the system performance is 3 dB worse than that of the DC-VLC-CC-CDMA system. Moreover, this parallel approach requires twice as many LEDs as the original system assumption to implement, increasing the complexity and cost of the system.

It can be seen from the above analysis that the method of increasing the DC gain has the best system performance, but it needs to be assumed that the system delays an integer number of chips, and the same performance cannot be achieved in the system where multipath interference exists. It needs to be assumed that the LED still works in the linear operating region after increasing the DC bias, whose requirements for the system components are more stringent. The U-VLC-CC-CDMA system can avoid the phenomenon of signal aliasing at the receiver, but its noise amplification makes the system performance worse by half, and the demand for LEDs is doubled. Although this polarity conversion method can meet the requirements of the VLC system for signal polarity, its requirements are relatively strict. Therefore, it is expected that a more rationalized VLC-CDMA system can be further designed.

5 Conclusions

This paper mainly proposes a VLC-CDMA system using complementary codes, and studies its transmitter and receiver models. The transmitter with multiple sub-codes architecture is designed. The single-user receiver with multiple sub-codes structure despreading is presented.

Aiming at the requirement of non-negative signals in VLC systems, a polarity conversion module is added to the system to realize unipolar processing of signals. U-VLC-CC-CDMA system is proposed, and the parallel implementation of the system is studied. Theoretical analysis shows that the parallel method can restore the signal, but the performance is worse 3 dB than that of DC-VLC-CC-CDMA system due to noise amplification. The parallel method requires twice as many LEDs of different wavelengths, which increases the system overhead and the difficulty of LED device achievability. The system simulation shows that the simulation curves of the unipolar processing method using complementary codes coincide with the theoretical curves, while the unipolar processing method using the Walsh sequences and the Gold sequences cannot overlap the theoretical curves due to their imperfect correlation.

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References

1. Komine, T., Nakagawa, M.: Fundamental analysis for visible-light communication system using LED lights. IEEE Trans. Consum. Electron. **50**(1), 100–107 (2004)
2. Memedi, A., Dressler, F.: Vehicular visible light communications: a survey. IEEE Commun. Surv. Tutorials **23**(1), 161–181 (2021)
3. Aboagye, S., Ngatched, T.M.N., Dobre, O.A.: Subchannel and power allocation in downlink VLC under different system configurations. IEEE Trans. Wireless Commun. **21**(5), 3179–3191 (2022)
4. Bariah, L., Elamassie, M., Muhaidat, S., et al.: Non-orthogonal multiple access-based underwater VLC systems in the presence of turbulence. IEEE Photonics J. **14**(1), 1–7 (2022)
5. Al Hammadi, A., Sofotasios, P.C., Muhaidat, S., et al.: Nonorthogonal multiple access for hybrid VLC-RF networks with imperfect channel state information. IEEE Trans. Veh. Technol. **70** (1), 398–411 (2021)
6. Qian, H., Dai, S.C., Zhao, S., Cai, S.Z., Zhang, H.: A robust CDMA VLC system against front-end nonlinearity. IEEE Photon. J. **7**(5), 7801809 (1–10) (2015)
7. Shoreh, M.H., Fallahpour, A., Salehi, J.A.: Design concepts and performance analysis of multicarrier CDMA for indoor visible light communications. J. Optical Commun. Netw. **7**(6), 554–562 (2015)
8. Chen, D., Wang, Q., Wang, J., et al.: Performance evaluation of ZCC and OZCZ code set in an integrated VLCP-CDMA system. IEEE Photonics Technol. Lett. **34**(16), 846–849 (2022)
9. Rahaim, M., Little, T.D.C.: Interference in IM/DD optical wireless communication networks. J. Optical Commun. Netw. **9**(9), D51–D63 (2017)
10. Chen Hsiao-Hwa: The Next Generation CDMA Technologies. 1st ed. John Wiley & Sons Ltd, (2007)
11. He, C., Yang, L.L., Xiao, P., Imran, M.A.: DS-CDMA assisted visible light communications systems. In: 20th IEEE International Workshop on Computer Aided Modeling and Design of Communication Links and Networks, pp. 27–32. IEEE, Guildford (2015)

12. Salvador, P., Valls, J., Corral, J.L., et al.: Linear response modeling of high luminous flux phosphor-coated white LEDs for VLC. J. Lightw. Technol. **40**(12), 3761–3767 (2022)
13. Salvador, P., Valls, J., Canet, M.J., et al.: On the performance and power consumption of bias-T based drivers for high speed VLC. J. Lightwave Technol. **40**(18), 6078–6086 (2022)
14. Tsonev, D., Sinanovic, Haas H: Novel unipolar orthogonal frequency division multiplexing (U-OFDM) for optical wireless. In: 75th IEEE Vehicular Technology Conference, pp. 1–5. IEEE, Yokohama (2012)
15. Wang, K., Liu, Y., Hong, Z., Zeng, Z.: Efficient timing offset estimation method tailored for ACO-OFDM VLC systems. J. Lightwave Technol. **40**(8), 2307–2320 (2022)
16. Mursley, P.: Performance evaluation for phase-coded spread-spectrum multiple-access communication cpart i: system analysis. IEEE Trans. Commun. **25**(8), 795–799 (1977)
17. Asahi Homepage. http://www.asahi-spectra.com/index.asp. Last accessed 20 Sept. 2022
18. Lausnay, S.D., Strycker, L.D., Goemaere, J.P., et al.: A test bench for a VLP system using CDMA as multiple access technology. In: 17th IEEE International Conference on Transparent Optical Networks, pp. 1–4. IEEE, Budapest (2015)
19. Cui, L., Tang, Y., Jia, H., et al.: Analysis of the multichannel WDM-VLC communication system. J. Lightwave Technol. **34**(24), 5627–5634 (2016)
20. Biagi, M., Pergoloni, S., Vegni, A.M.: LAST: A framework to localize, access, schedule, and transmit in indoor VLC systems. J. Lightwave Technol. **33**(9), 1872–1887 (2015)
21. Qiu, Y., Chen, H.-H., Li, J., Meng, W.: VLC-CDMA systems based on optical complementary codes. IEEE Wirel. Commun. **27**(1), 147–153 (2020)
22. Lee, K., Park, H., Barry, J.R.: Indoor channel characteristics for visible light communications. IEEE Commun. Lett. **15**(2), 217–219 (2011)
23. Komine, T., Lee, J.H., Haruyama, S., et al.: Adaptive equalization system for visible light wireless communication utilizing multiple white LED lighting equipment. IEEE Trans. Wireless Commun. **8**(6), 2892–2900 (2009)