# Research on Indoor Visible-Light Communications System with Carrier Interferometry OFDM

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***Abstract*—In order to enhance the overall performance of the visible light communications system and to achieve the efficient use of spectrum resources, by leveraging the characteristic of channel frequency selection, we propose a novel visible light communications system based on Carrier Interferometry Orthogonal Frequency Division Multiplexing (CI-OFDM) transmission scheme. Through the frequency domain diversity, the system performance can be efficiently improved. At the same time, with a meticulous designed CI codes, the system Peak-Average Power Ratio (PAPR) can be effectively reduced. Analysis and simulation results demonstrate that, under the same Signal to Noise Ratio (SNR) condition, the proposed CI-OFDM scheme performs significantly better in BER than the traditional OFDM system, and greatly reduces the PAPR of the transmitted signal.**

***Index Terms*—Visible light communication; CI-OFDM; PAPR.**

## I. Introduction

Wireless communication has become not only a pillar of the world high-tech industry, but also an essential part for global development of informationization. However, it still faces the problem of system capacity expansion under the existent technology, which contradicts with the explosive growth of the growing business demand [1]. Visible light communications will provide an effective way to address the above problem. The high-speed flashes of light and dark signals issued by the light-emitting diode, which transmit information, cannot be perceived by the naked eye but can be captured by the photoelectric detector device. Therefore, the data transmission can be supplied simultaneously with regular illumination. Furthermore, the visible light communication is immune from complicated electromagnetic interference to provide a very rich spectrum of resources (extra wide spectral band of approximately 375THz, 1THz = 1000GHz) for high-capacity communications services [2].

However, in the visible light communication system, in order to achieve better communication and illumination effects, and to prevent the ”shadow” being produced, it is common to arrange multiple Light Emitting Diode (LED) lights. Thus, the light pulses of signal can be overlapped in time and received by detectors through different transmission paths, resulting in the occurrence of Inter Symbol Interference (ISI), which requires an in-depth study of signal processing methods to overcome it. Multi-carrier Orthogonal Frequency Division Multiplexing (OFDM) technology modulates the high-speed serial data in parallel onto multiple orthogonal subcarriers to reduce the code rate and the impact of ISI. At the same time, a protection interval is inserted between each OFDM symbol to further eliminate the residual ISI [3]. However, the visible light OFDM system has its own inherent shortcomings. For example, without frequency diversity, the bit error rate is severely affected by the zero channel spectrum, and the Peak to Average Power Ratio (PAPR) is so large that the amplifier nonlinear problem is launched [4][5].

To further enhance the overall performance of visible light communication system, this paper introduces the Carrier Interferometry OFDM (CI-OFDM) modulation technology into the visible light communication systems. Different from the visible light OFDM scheme, in the CI-OFDM transmission, the data after the constellation mapping and the serial to parallel conversion is not just for their respective sub-carrier modulation, but is simultaneously transmitted on all sub-carriers. In order to enable the receiver to separate the different simultaneous transmitted data, all the data are multiplied by mutually orthogonal CI code during modulation. Research shows that, through the frequency domain diversity, the above transmission technology can on one hand effectively improve the visible light transmission quality, on the other hand, the CI code allows each data modulation is evenly staggered in the time-domain waveform, instead of as a random sum of multiple sinusoidal signals in the OFDM, which can effectively reduce the OFDM transmission signal PAPR. Therefore, CI-OFDM can be potentially applied as a multi-carrier transmission scheme in visible light communication system.

The rest of the paper is organized as follows: The system structure and principle are presented in Section 2. In Section 3, the performance analysis is performed. The simulation results of our system are showed in Section 4. Finally, the conclusion is drawn in Section 5.

## II. System Structure and Principle

### A. CI Code and CI-OFDM

The concept of CI code was firstly proposed by Nassar, et al. in 1999 [6]. It was then regarded as a new multiple access technique and applied in the multi-carrier systems. The

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CI code that is formulated by the row vectors of the Fourier matrix is given as

$$\mathbf{C}_N = [W_{i,k}]_{N\times N}, \tag{1}$$

where $W_{i,k} = \exp\left(\frac{2\pi\sqrt{-1}}{N}ik\right), 0 \le i,k \le N-1$, and each vectors of $\mathbf{C}_N$ is orthogonal with the others. The $i$th CI code word $\mathbf{c}_i(0 \le i \le N-1)$ is the $i$th row vector of $\mathbf{C}_N$, denoted as

$$\begin{aligned} \mathbf{c}_i &= \left(c_i^0, c_i^1, \cdots, c_i^{N-1}\right) \\ &= \left(W_{i,0}, W_{i,1}, \cdots, W_{i,N-1}\right). \end{aligned} \tag{2}$$

The basic idea of CI-OFDM is demonstrated in Fig.1. The transmitted symbol is firstly converted into $N$ symbols in parallel. Each symbol is then extended onto a CI code sequence with the length of $N$, which is then modulated by $N$ subcarriers. The CI code for each symbol is unique, and is orthogonal with all the others CI-codes. At the receiver, the orthogonality of the CI codes is utilized to demodulate each symbol.

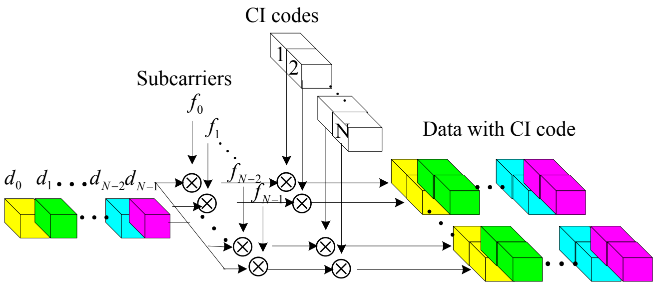


Fig. 1. Basic Idea of CI-OFDM

### B. Visible-Light CI-OFDM Communication System

The baseband model of visible-light CI-OFDMA communication system is given in Fig.2. At the transceiver, the input bits are mapped into the constellation, which forms the data stream $d_1, d_2, \cdots$. Then the serial data stream is converted into parallel form, and data $d_i$ is modulated by the $N$th subcarrier. At the receiver, in order to separate $N$ data transmitted simultaneously , each data $d_i$ times the corresponding $\mathbf{c}_i$ during the modulation period and the complete CI-OFDM symbol is presented as $\sum_{i=0}^{N-1} d_i\mathbf{c}_i$. To mitigate the ISI caused by multipath effect, the cyclic prefix(CP) is added and the CP should be longer than the delay spread of the multi-path channel. Finally, the discrete CI-OFDM symbol $s(n)$ is achieved by the serial-parallel conversion. During IM/DD visible-light transmission, proper direct component is usually needed to warrant a positive signal.

After transmitted in the optical channel $h(n)$, the CI-OFDM symbol received is given as

$$r(n) = \Re s(n) \otimes h(n) + w(n). \tag{3}$$

$w(n)$ is the additive white Gaussian noise(AWGN), $\Re$ is the efficiency of photoelectric detection, and $\otimes$ means convolution.

At the receiver of the system, PD receives the light signals transmitted by the white-light LED and converts it into electrical signals. After the serial-parallel conversion, the CP is eliminated. Each subcarrier is then compensated for the channel and the phase offsets, and finally all the estimation values are combined. In Fig.2, $\omega_k$ denotes the weight of the $k$th subcarrier, and it is determined by the combination scheme. For the MMSE combination, for instance,

$$\omega_k = \frac{A\alpha_k}{{\alpha_k}^2 + \sigma^2}, \tag{4}$$

where $A$ is a constant representing the normalized energy per bit; $\alpha_k$ is the amplitude of the channel for subcarrier $k$; and $\sigma^2$ is the variance of the noise.

## III. Performance Analysis

### A. Bit Error Rate (BER) Analysis

The CI code of data $d_i$ is expressed as equation (2), and then the received signals for the visible-light CI-OFDM system in the frequency selective fading scenario is formulated as

$$\begin{aligned} r(t) = \mathrm{Re}\Bigg[ &\sum_{l=0}^{N-1}\sum_{k=0}^{N-1} E_b \cdot \alpha_k(t) \cdot d_l \cdot c_l^k \cdot p(t) \cdot \\ &e^{j(2\pi f_k t + \theta_k(t))} \Bigg] + n(t). \end{aligned} \tag{5}$$

The constant $E_b$ is the normalized energy per bit. The frequency $f_k$ is defined as $f_k = f_c + k/T_s$, where $T_s$ is the period per symbol. $p(t)$ is a rectangular pulse during $[0, T_s]$. $\alpha_k$ and $\theta_k$ are the altitude and phase of the channel response for the $k$th subcarrier respectively. $n(t)$ is the AWGN with a mean of zero and a power spectrum density of $N_0/2$.

When the demodulation and combination are completed at the receiver of the visible-light CI-OFDM system, the obtained variable to be determined for $d_i$ is

$$\begin{aligned} \xi_i &= \sum_{m=0}^{N-1}\sum_{l=0}^{N-1}\sum_{k=0}^{N-1} \omega_m E_b d_l c_l^k \left(c_l^k\right)^* \rho_{k,m} + \sum_{m=0}^{N-1} \omega_m \cdot n_m \\ &= S + I_{OS} + I_{SO} + I_{ICI} + \eta, \end{aligned} \tag{6}$$

where

$$\rho_{k,m} = \frac{1}{T_s}\int_0^{T_s} \alpha_k \cos\left[2\pi\left(f_k - f_m - \varepsilon\right)t + \theta_k - \widehat{\theta}_m\right] dt. \tag{7}$$

In (7), $\varepsilon$ is a constant and it stands for the frequency offset. $\widehat{\theta}$ is the estimation of the phase. In (6), the weight for combination of the $m$th subcarrier is $\omega_m$, and it is determined by the combination scheme. $\eta = \sum_{m=0}^{N-1} \omega_m \cdot n_m$ denotes noise, while $S$ is the desired signal. The interferences $I_{OS}$, $I_{SO}$, and $I_{ICI}$ are the interference from other users on the same subcarrier, the interference brought about by other subcarriers, and the interference caused by different data transmitted on different subcarriers respectively.

When $l = i$ and $k = m$, $S$ is given as

$$S = Ad_i \cdot \frac{\sin\left(\pi N\overline{\varepsilon}\right)}{\pi N\overline{\varepsilon}} \sum_{m=0}^{N-1} \omega_m \alpha_m, \tag{8}$$

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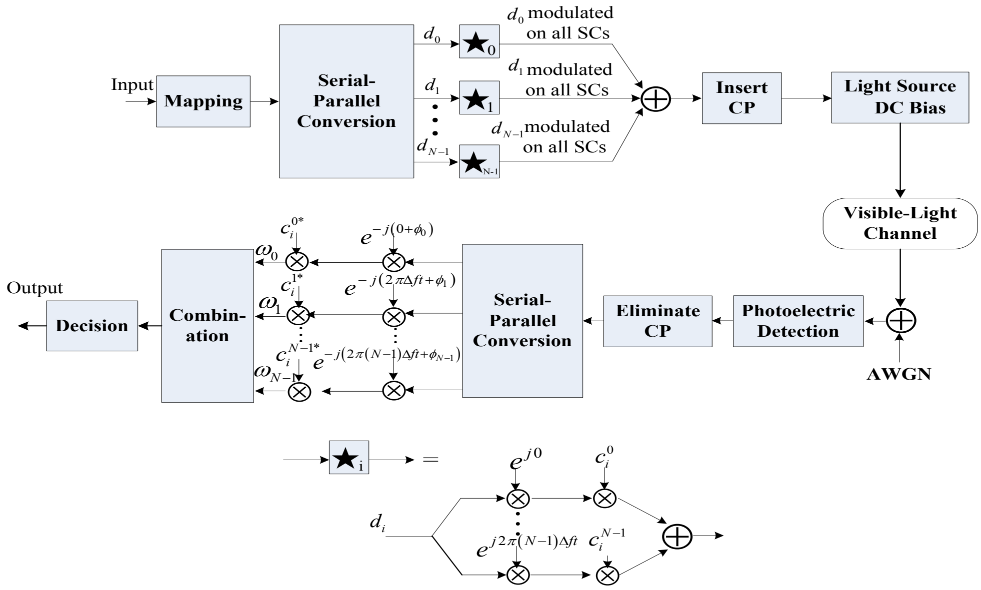


Fig. 2. The baseband model of visible-light CI-OFDM communication system

where $\overline{\varepsilon}$ is the normalized frequency offset throughout the whole band and the estimation of the phase is got by $\widehat{\theta}_k = -\pi N\overline{\varepsilon} + \theta_k \bmod 2\pi$.

When $l \neq i$ and $k = m$, $I_{OS}$ is given as

$$I_{OS} = E_b \frac{\sin(\pi N\overline{\varepsilon})}{\pi N\overline{\varepsilon}} \sum_{l=0,l\neq i}^{N-1} \sum_{m=0}^{N-1} d_l \omega_m \alpha_m c_l^m (c_l^m)^*. \quad (9)$$

When $l = i$ and $k \neq m$, $I_{SO}$ is given as

$$I_{SO} = E_b d_i \cdot \sum_{m=0}^{N-1} \sum_{k=0,k\neq m}^{N-1} \omega_m \alpha_k c_l^m (c_l^m)^* \zeta_{m,k}. \quad (10)$$

where

$$\zeta_{m,k} = \frac{\sin(\pi N\overline{\varepsilon})}{\pi(m-k+N\overline{\varepsilon})} \cos(\theta_m - \theta_k). \quad (11)$$

When $l \neq i$ and $k \neq m$, $I_{ICI}$ is given as

$$I_{ICI} = E_b \sum_{l=0,l\neq i}^{N-1} d_l \sum_{m=0}^{N-1} \sum_{k=0,k\neq m}^{N-1} \omega_m \alpha_k c_l^m (c_l^m)^* \zeta_{m,k}. \quad (12)$$

Afterward, the signal to interference and noise ratio (SINR) is given as

$$SINR = \frac{P_S}{P_{OS} + P_{SO} + P_{ICI} + P_\eta} \cdot \quad (13)$$

Here $P_S$, $P_{OS}$, $P_{SO}$, $P_{ICI}$ and $P_\eta$ are power for $S$, $I_{OS}$, $I_{SO}$, $I_{ICI}$ and the noise $\eta$. According to the Gaussian approximation, the BER is readily given as

$$Pe = \int_0^\infty Q\left(\sqrt{SINR}\right) p(SINR)\, d(SINR) \cdot \quad (14)$$

## B. Peak-to-Average Power Ratio (PAPR) Analysis

In this section, the PAPR of visible-light CI-OFDM system is analyzed. Without loss of generality, let $E_b = \frac{1}{\sqrt{N}}$, and the equivalent baseband form for the transmitted signals in one OFDM symbol period is achieved by

$$s(t) = \frac{1}{\sqrt{N}} \sum_{l=0}^{N-1} \sum_{k=0}^{N-1} d_l \cdot c_l^k \cdot e^{j2\pi kt/T_s}. \quad (15)$$

According to [?], the average power of $S(t)$ is $N$, which means $\mathbf{E}\left[|\mathrm{s}(\mathrm{t})|^2\right] = \mathrm{N}$ ($\mathbf{E}$ means the mathematical expectation), and the instantaneous power of $s(t)$ can be expressed as

$$|s(t)|^2 = N + \tfrac{2}{N}\mathrm{Re}\left\{\sum_{k=1}^{N-1}\left(\sum_{l=0}^{N-1} R_l[k] + \sum_{l=0}^{N-1}\sum_{l'=0,l'\neq l}^{N-1} d_l (d_{l'})^* Z_{l,l'}[k]\right) e^{j2\pi kt/T_s}\right\}, \quad (16)$$

where

$$R_l[k] = \sum_{m=0}^{N-k-1} c_l^m \left(c_l^{m+k}\right)^*, \quad (17)$$

$$Z_{l,l'}[k] = \sum_{m=0}^{N-k-1} c_l^m \left(c_{l'}^{m+k}\right)^*. \quad (18)$$

$R_l[k]$ is defined as the partial autocorrelation function of the $l$th CI code, while $Z_{l,l'}[k]$ is the partial cross-correlation function for the $l$th and the $l'$th spread spectrum code.

As for (16), the envelop of the CI-OFDM transmitted signal is determined by $R_l[k]$, $Z_{l,l'}[k]$ and information sequence $d_l$. According to the definition of PAPR, we use $P$ to stands for the PAPR, and it is given as

$$\begin{aligned} P &= \frac{\max\limits_{0\le t\le T_s} |s(t)|^2}{\mathrm{E}\left[|s(t)|^2\right]} = \frac{\max\limits_{0\le t\le T_s} |s(t)|^2}{N} \\ &= \max_{0\le t\le T_s}\left[1+\frac{2}{N^2}\mathrm{Re}\left\{\sum_{k=1}^{N-1}\left(\sum_{l=0}^{N-1} R_l\left[k\right]+ \right.\right.\right. \\ &\left.\left.\left.\sum_{l=0}^{N-1}\sum_{l'=0,l'\neq l}^{N-1} d_l(d_{l'})^* Z_{l,l'}\left[k\right]\right)e^{j2\pi kt/T_s}\right\}\right] \end{aligned} \quad (19)$$

Due to the orthogonality among different CI codes, we have

$$\begin{aligned} \sum_{l=0}^{N-1} R_l\left[k\right] &= \sum_{l=0}^{N-1}\sum_{m=0}^{N-k-1} c_l^m\left(c_l^{m+k}\right)^* \\ &= \sum_{m=0}^{N-k-1}\sum_{l=0}^{N-1} c_l^m\left(c_l^{m+k}\right)^* = 0 \end{aligned}, \quad (20)$$

which means the PAPR of CI-OFDMA is determined only by the partial cross-correlation function and the information sequence. With BPSK being utilized, $d_l \in \{-1, 1\}$, and the upper bound of PAPR is further given as

$$\begin{aligned} P &= 1+\frac{2}{N^2}\max_{0\le t\le T_s}\mathrm{Re}\left\{\sum_{k=1}^{N-1}\sum_{l=0}^{N-1}\sum_{l'=0,l'\neq l}^{N-1} d_l(d_{l'})^* \cdot \right. \\ &\left. Z_{l,l'}\left[k\right]e^{j2\pi kt/T_s}\right\} \\ &\le 1+\frac{2}{N^2}\max_{0\le t\le T_s}\left|\sum_{k=1}^{N-1}\sum_{l=0}^{N-1}\sum_{l'=0,l'\neq l}^{N-1} d_l(d_{l'})^* Z_{l,l'}\left[k\right]e^{j2\pi kt/T_s}\right| \\ &\le 1+\frac{2}{N^2}\max_{0\le t\le T_s}\sum_{k=1}^{N-1}\left|\sum_{l=0}^{N-1}\sum_{l'=0,l'\neq l}^{N-1} d_l(d_{l'})^* Z_{l,l'}\left[k\right]\right| \\ &\le 1+\frac{2}{N^2}\max_{0\le t\le T_s}\sum_{k=1}^{N-1}\sum_{l=0}^{N-1}\sum_{l'=0,l'\neq l}^{N-1}\left|Z_{l,l'}\left[k\right]\right| = Q \end{aligned} \quad (21)$$

On the basis of the partial cross-correlation function, the equation (21) gives out the upper bound $Q$ for the PAPR using BPSK modulation.

## IV. Simulation Results

The visible-light communication is a new type of wireless communication approach, and hence measuring and modeling its channel model is still under investigation. Therefore, there is no such multi-path wireless channel model that is universally acknowledged internationally. On the consideration that the modeling of the channel is not the key point of this paper, we adopt the channel model used in [7]. In such a model, the simulation is carried out in a room with the length of 6m, width of 6m and height of 3m. The coordinators of the transceiver and the receiver are (3,3,3) and (1,3,1) respectively. This scenario is given in Fig.3.

As for this scenario, [7] achieved the impulse response for the multi-path channel via the combination of computer simulation and physical concepts. The impulse response is given as

$$h\left(t\right) = 5.8H\left(0\right)\left(\frac{11.0561\tau_{rms}}{t+11.0561\tau_{rms}}\right)^6 u\left(t\right)\cdot \quad (22)$$

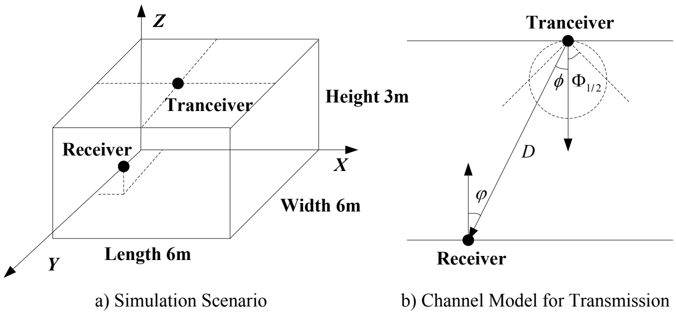


Fig. 3. Simulation scenario and optical channel model for transmission

$H\left(0\right)$ is a DC gain for the line-of-sight(LOS) link, and it is calculated as

$$H\left(0\right) = \begin{cases} \frac{(m+1)A}{2\pi D^2}\cos^m\left(\phi\right)T_s\left(\varphi\right)g\left(\varphi\right)\cos\left(\varphi\right), & 0\le\varphi\le\psi_c \\ 0, & \varphi>\psi_c \end{cases} \quad (23)$$

where $A$ is the receiving area for the photoelectric detector. $D$ is the distance between the transceiver and the receiver. $\phi$ is the emission angle, while $\varphi$ is the incidence angle. $T_s\left(\varphi\right)$ is the gain for the optical filter and $g\left(\varphi\right)$ is the gain for optical concentrator. $\psi_c$ is the FOV of the receiver. $m = -\frac{\ln 2}{\ln\cos\Phi_{1/2}}$ is the radiation mode of the light source, and $\Phi_{1/2}$ is named the half-angle of the transmission power. The simulation parameters is given in table 1.

TABLE I
System Parameters for Simulation

| Parameters | Values |
|---|---|
| Central lightening power of LED | 30mW |
| FOV of the receiver) | 60° |
| Half-angle of the transmission power | 60° |
| Area of the photoelectric detector | $1\text{cm}^2$ |
| Refractive index of the optical concentrator | 1.5 |
| Efficiency of the photoelectric detector | 0.5(A/W) |
| Reflection index of the reflection plane | 0.8 |
| Room size (length×width×height) | 6m×6m×3m |
| Transceiver coordinator | (3,3,3) |
| Receiver coordinator | (1,3,1) |
| Number of subcarriers | 128 |

Fig.4 gives the comparison of the BER between visible-light CI-OFDM and visible-light OFDM using MMSE combination and BPSK modulation. Simulation results show that, the performance of CI-OFDM outperforms OFDM obviously. For instance, for the required BER of $10^{-3}$, visible-light CI-OFDM has a gain of 1dB concerning SNR.

In the CI-OFDM system, CI-codes make the peaks of signal waves staggered from each other in time domain. This is quite different from OFDM whose symbol is the sum of many stochastic sine waves and solve the PAPR problem in OFDM systems. Fig.5 plots the PAPR distribution of the white-light signal for both OFDM and CI-OFDM systems. From the

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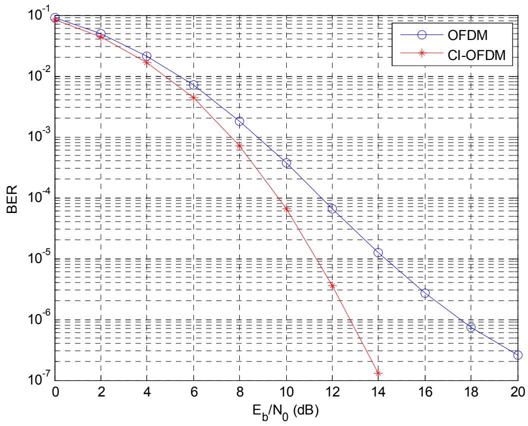
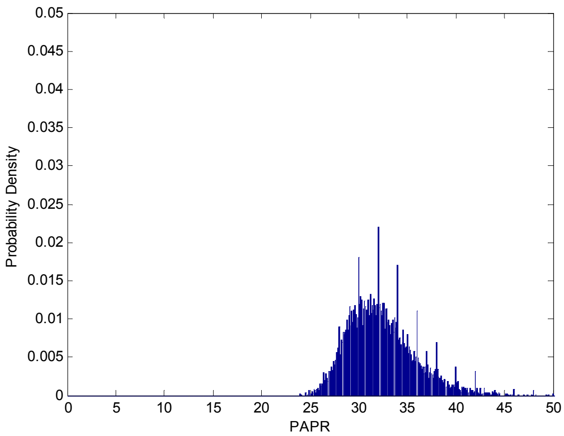
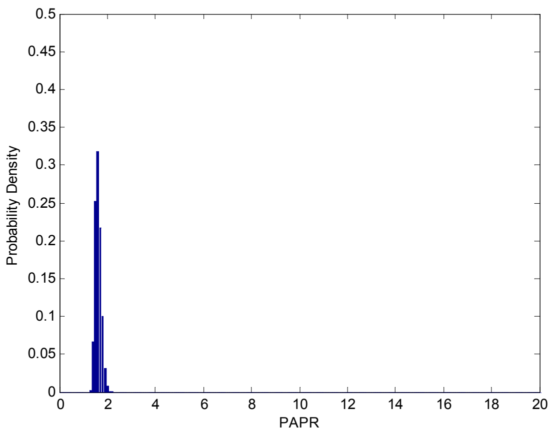



Fig. 4. BER performance of visible-light CI-OFDM and OFDM systems

results, it can be seen that the visible-light CI-OFDM can obviously reduce the PAPR of OFDM systems.




(a) PAPR distraibution of the white-light signal in OFDM system




(b) PAPR distraibution of the white-light signal in CI-OFDM system

Fig. 5. PAPR performance of visible-light CI-OFDM and OFDM systems

## V. Conclusion

In this paper, we propose a visible-light communication system and corresponding transmission scheme based on CI-OFDM, which can function as an effective technique enhancing the performance of visible-light communication system. Simulation results show that for a required BER of $10^{-3}$ in the frequency selective channel, the visible-light CI-OFDM can yield 1dB gain of SNR. Simultaneously, this method can effectively reduce PAPR with the help of CI codes.

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