Bandwidth-Efficient Precoding Scheme with Flicker Mitigation for OFDM-Based Visible Light Communications

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Recently, orthogonal frequency-division multiplexing (OFDM) was applied to VLC systems owing to its high rate capability. On the other hand, a real-valued unipolar OFDM signal for VLC significantly reduces bandwidth efficiency. For practical implementation, channel estimation is required for data demodulation, which causes a further decrease in spectral efficiency. In addition, the large fluctuation of an OFDM signal results in poor illumination quality, such as chromaticity changes. This paper proposes a spectrally efficient method based on a hidden-pilot-aided precoding technology for VLC with less flickering than a conventional OFDM-based method. This approach can obtain channel information without any loss of bandwidth efficiency while ensuring illumination quality by reducing the flickering effect of an OFDM-based VLC. The simulation results show that the proposed method provides a 6.4% gain in bandwidth efficiency with a 4% reduction in flicker compared to a conventional OFDM-based method.

Keywords: Visible light communication, VLC, orthogonal frequency-division multiplexing, OFDM, bandwidth efficiency, clipping, flickering.

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I. Introduction

Visible light communication (VLC) systems have recently attracted considerable attention in the field of high-speed optical wireless communications [1]–[6]. Compared to conventional wireless systems, light-emitting diode (LED) lighting has many advantages, such as huge unregulated bandwidth for higher data rates and no interference between channels operating in adjacent rooms.

For data modulation of earlier VLC systems, pulse-based optical wireless systems using intensity modulation with direct detection (IM/DD) are most popular because of their simplicity and low-cost implementation. On the other hand, the existence of multiple wireless paths results in multipath distortion and intersymbol interference (ISI), which require the use of complex equalization techniques in systems that employ IM/DD.

Recently, it was reported that multiple-subcarrier modulation (MSM) can provide efficient immunity to multipath distortion and fluorescent-light noise near dc sources [7]. As one of the implementation methods of MSM, the use of orthogonal frequency-division multiplexing (OFDM) has been considered because it can provide high-speed communications and efficiently combat ISI [8]–[10]. In the relevant literature, three methods have mainly been discussed to ensure a real-valued unipolar OFDM signal for VLC — ACO-OFDM, DCO-OFDM, and DMT-OFDM [11]–[13].

Considering practical OFDM systems, the most significant problems of real-valued unipolar OFDM can be divided into two groups. The first is related to the occurrence of low spectral efficiency due to both the Hermitian symmetry condition to generate a real-valued signal and the pilot symbol insertion for channel estimation. The other is related to the occurrence of noticeable degradation of illumination quality, such as chromaticity changes due to flickering caused by the large fluctuations of OFDM-based VLC signals [14]–[15].

Pilot-symbol-aided modulation (PSAM) is widely used in practical implementations for channel tracking [16]. Because the number of subcarriers reserved for pilot tones must be greater than the number of channel taps, PSAM leads to a significant spectral loss, motivating researchers to use blind and semiblind methods instead [17]–[18]. Despite this, these methods may not be effective because of their high implementation complexity and relatively low estimation accuracy. A hidden pilot-aided precoding (HP) scheme provides an efficient solution for such problems by developing a linear precoder and superimposed pilot vector based on a design of polyphase sequences [19]. In addition to the advantage of bandwidth efficiency, it retains a relatively low dynamic range of signals due to a certain amount of power allocated to a pilot vector. Therefore, it is robust to the brightness-flickering problems caused by the large fluctuations found in OFDM-based VLC signals; no study has considered the spectral efficiency issue together with the illumination quality of OFDM-based VLC.

In this paper, the performance improvement of a hidden pilot-aided precoding scheme for VLC (HP-VLC) is designed and investigated. In contrast to the previous HP scheme, which was solely applicable to RF communications [19], a new precoder and a hidden pilot structure are developed to retain VLC constraints such as those of real-valued and positive OFDM modulated symbols for data transfer via LED light, and a dc bias to control the dimming level for lighting functionality. Unlike a conventional PSAM-based VLC scheme, the proposed HP-VLC can provide channel estimation without loss of bandwidth efficiency and support good illumination quality because of the relatively low dynamic range of a modulated signal. This approach is particularly well-suited to VLC applications, where a high data rate and strict regulation of LED flicker are required. Computer simulations confirm that the proposed scheme outperforms the conventional scheme based on PSAM with respect to both bandwidth efficiency and illumination quality.

The remainder of this paper is organized as follows. Section II presents a detailed signaling model. Section III shows the proposed HP-VLC method. Section IV derives the channel estimation and symbol detection processes. Section V addresses the importance of illumination quality and introduces a performance metric. The numerical results are reported in Section VI, and Section VII contains our conclusions.

II. Signaling Model

A model for a received signal of a general VLC system can be expressed as follows:

$$r[n] = \varphi \bar{x}[n] \otimes h[n] + w[n], \quad (1)$$

where $\otimes$ denotes a convolution operator, φ is the photo-detector responsivity, $\bar{x}[n]$ is the transmitted intensity-modulated signal, $h[n]$ is the channel impulse response, $w[n]$ is noise, and $r[n]$ is the received photocurrent. Although the above equation is a general linear filter channel model with additional noise, VLC systems differ from conventional wireless systems in that an input signal $\bar{x}[n]$ represents the instantaneous optical power and is a non-negative value.

Without a loss of generality, $\varphi = 1$ was set for simplicity. Because shot noise, which is caused by high-intensity ambient light, is the dominant noise source in VLC channels, it can be modelled as an additive white Gaussian noise distributed with variance $\sigma_{\mathbf{w}}^2$, where $\mathbf{w} = [w[0], w[1], \ldots, w[N-1]]$.

The system model discussed in this study is depicted in Fig. 1. In an OFDM system, a discrete time-domain signal, $\mathbf{x} = [x[0], x[1], \ldots, x[N-1]]^{\mathrm{T}}$, is generated by applying an inverse discrete Fourier transform (IDFT) operation to a frequency-domain signal, $\mathbf{x}_{\mathrm{F}} = [x_{\mathrm{F}}[0], x_{\mathrm{F}}[1], \ldots, x_{\mathrm{F}}[N-1]]^{\mathrm{T}}$, which can be shown as

$$x[n] = \mathrm{IDFT}\left(x_{\mathrm{F}}[k]\right) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} x_{\mathrm{F}}[k] \exp\left(\frac{\mathrm{j}2\pi kn}{N}\right), \quad (2)$$

where N is the size of the IDFT. In a VLC system using LEDs, the optical signal used to run an LED driver must be a real and unipolar value. According to a symmetry property of IDFT, a real-valued time-domain signal, $x[n]$, corresponds to a frequency-domain signal, $x_{\mathrm{F}}[k]$, which is known as Hermitian symmetry and is expressed as

$$\begin{aligned} x_{\mathrm{F}}[k] &= x_{\mathrm{F}}^{*}\left[2(M+1)-k\right], \\ x_{\mathrm{F}}[0] &= x_{\mathrm{F}}[M+1] = 0, \end{aligned} \quad (3)$$

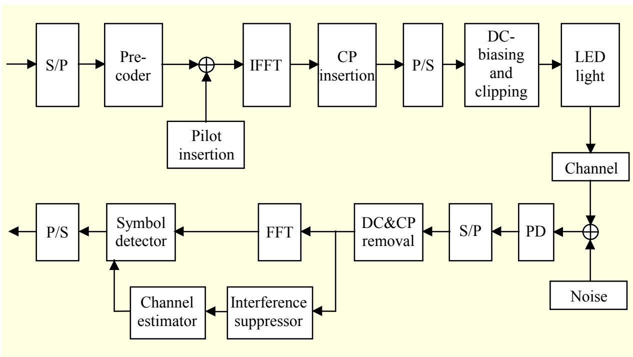

Fig. 1. System model of proposed HP-VLC.

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where * denotes the complex conjugate, $N = 2(M+1)$, and $1 \le k \le 2M+1$.

III. Proposed HP-VLC Scheme

For the purposes of high bandwidth efficiency and ensuring that OFDM signals are applicable to VLC systems, an HP-VLC scheme simultaneously uses a linear precoder and hidden pilot vector. Therefore, there is inherent interference between the data to be transmitted and the pilot vector. To remove this interference for the purposes of retaining an accurate channel prediction, the designs of both a linear precoder and a pilot vector based on orthogonal polyphase sequences, which have good periodic autocorrelation and cross-correlation properties, are considered. Note that the interference between the data and pilot symbols can be reduced because cyclic-shifted versions of polyphase sequences remain orthogonal to one another.

To design both a linear precoder and a hidden pilot vector, a polyphase sequence of length $M = p^r - 1$, where p is a prime number and r is an integer, is considered. By generating M polyphase sequences such that $\mathbf{C} = [\mathbf{c}_0, \mathbf{c}_1, \ldots, \mathbf{c}_{M-1}]^{\mathrm{T}}$, the $(M+1)\times(M-1)$ linear precoder matrix, $\mathbf{P}$, and $(M+1)\times 1$ hidden pilot vector, $\mathbf{t}$, can be derived as follows:

$$\begin{aligned} \mathbf{P} &= \mathbf{F}\cdot\left[\mathbf{c}'_0, \mathbf{c}'_1, \ldots, \mathbf{c}'_{M-2}\right], \\ \mathbf{t} &= \mathbf{F}\mathbf{c}'_{M-1}, \end{aligned} \tag{4}$$

where $\mathbf{F}$ is a discrete Fourier transform (DFT) matrix and $\mathbf{c}' = \left[\mathbf{c}^{\mathrm{T}}, 0\right]^{\mathrm{T}}$ is an $(M+1)\times 1$ vector.

The frequency-domain transmit symbol block, which exploits both a linear precoder matrix and a pilot vector, is set to $\mathbf{X} = \overline{\mathbf{P}}\overline{\mathbf{s}} + \overline{\mathbf{t}}$, where $\overline{\mathbf{s}}$ is a $2(M-1)\times 1$ total information data block. The linear precoder matrix $\overline{\mathbf{P}}$ is designed such that

$$\overline{\mathbf{P}} = \begin{bmatrix} \hat{\mathbf{P}} & \mathbf{0}_{M\times(M-1)} \\ \mathbf{0}_{M\times(M-1)} & \hat{\mathbf{P}} \end{bmatrix}, \tag{5}$$

where

$$\hat{\mathbf{P}} = \begin{bmatrix} \underline{\mathbf{0}} \\ \mathbf{P} \end{bmatrix},$$

and $\underline{\mathbf{0}}$ is a $1 \times (M-1)$ zero vector. The *total* pilot vector is defined as $\overline{\mathbf{t}} = \left[0 \;\; \mathbf{t}^{\mathrm{T}} \;\; 0 \;\; \tilde{\mathbf{t}}^{\mathrm{T}}\right]^{\mathrm{T}}$, where $\tilde{\mathbf{t}}$ is the complex conjugate of $\mathbf{t}$ with the order of its elements reversed. The total information data block $\overline{\mathbf{s}}$ consists of a data vector and its Hermitian symmetry, $\overline{\mathbf{s}} = \left[\mathbf{s}^{\mathrm{T}} \;\; \hat{\mathbf{s}}^{\mathrm{T}}\right]^{\mathrm{T}}$, where $\hat{\mathbf{s}}$ is the complex conjugate of the data vector $\mathbf{s}$.

The IDFT block, $\mathbf{F}^{\mathrm{H}}$, is used to carry out OFDM modulation. A CP is then inserted into each OFDM symbol in the time domain. The discrete time-domain signal $\mathbf{x}$ is given by

$$\mathbf{x} = \mathbf{F}^{\mathrm{H}}\overline{\mathbf{P}}\overline{\mathbf{s}} + \mathbf{F}^{\mathrm{H}}\overline{\mathbf{t}} = \overline{\mathbf{A}}\overline{\mathbf{s}} + \overline{\mathbf{b}}. \tag{6}$$

Note that the discrete time-domain signal tends to provide a large range of both negative and positive amplitudes and has real-valued bipolar elements.

A VLC system is limited by the dynamic range of the LEDs it employs. This means that a signal outside of this range will be clipped. Here, it was assumed that the nonlinear characteristics of LEDs can be compensated for by a digital predistortion process. An LED can then be linearized within the interval $[g_{\mathrm{l}}, g_{\mathrm{u}}]$, where g_{u} denotes the upper clipping level and g_{l} denotes the lower clipping level.

Here, an LED input signal, $\overline{x}[n]$, which is non-negative and has a limited dynamic range, is obtained from $x[n]$ after implementing both a clipping and a biasing operation. The dynamic range of $\overline{x}[n]$ is defined as $\tau_{\overline{\mathbf{x}}} = g_{\mathrm{u}} - g_{\mathrm{l}}$.

To satisfy the amplitude non-negativity constraint of the LED input signal $\overline{x}[n]$, a dc bias is required. In OFDM-based VLC, LED dimming can be controlled using this bias. Considering the clipping and biasing operations, the LED input signal within the dynamic range can be expressed as

$$\overline{x}[n] = \begin{cases} g_{\mathrm{u}} & x[n] \ge g_{\mathrm{u}}, \\ x[n] + \beta[n] & g_{\mathrm{u}} \le x[n] \le g_{\mathrm{l}}, \\ g_{\mathrm{l}} & x[n] \le g_{\mathrm{l}}, \end{cases} \tag{7}$$

where $\beta[n]$ is a dc bias used to ensure non-negativity. Note that a distortion of the OFDM signals caused by the clipping operation is strongly dependent upon the dc bias. Therefore, a conventional OFDM is of limited use in VLC systems where high average optical powers are required for high target dimming.

To quantify the dc bias related to the LED dynamic range, let us define a biasing ratio, δ, as follows:

$$\delta = \frac{\beta}{g_{\mathrm{u}} - g_{\mathrm{l}}}. \tag{8}$$

Figure 2 shows the signal variance of the clipped OFDM signal as a function of the biasing ratio. To provide a sufficient range of dc-bias with regard to the dynamic range, this study considered biasing ratios ranging from 0.1 to 0.9. The figure shows that clipping becomes significant as the biasing ratio approaches 0.1 or 0.9; hence, the signal variance decreases.

The now clipped and dc-biased OFDM signal is emitted through the intensity of an LED. At the receiving end, a photodiode converts the incoming optical signal to an electrical signal and transforms it to a digital domain for digital signal processing. To eliminate the effect of dc-bias, the average amplitude of the incoming LED signal is removed. In vector form, the incoming optical signal with dc-bias removal can be

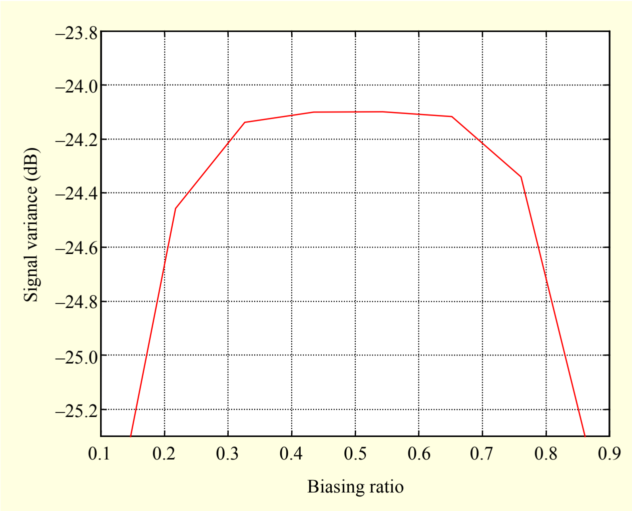

Fig. 2. Signal variance according to biasing ratio.

expressed as

$$\mathbf{k} = \mathbf{H}_c\mathbf{F}^{\mathrm{H}}\bar{\mathbf{x}} + \mathbf{w} = \mathbf{H}_c\bar{\mathbf{A}}\bar{\mathbf{s}} + \mathbf{H}_c\bar{\mathbf{b}} + \mathbf{w}, \tag{9}$$

where $\mathbf{w}$ denotes a shot noise vector modeled as an additive white Gaussian noise with variance σ_{w}^2. A cyclic prefix is then removed and the OFDM symbol block is demodulated using a DFT matrix ($\mathbf{F}$). An $N \times 1$ demodulated symbol vector, $\mathbf{r}$, can be expressed as

$$\mathbf{r} = \mathbf{F}\mathbf{H}_c\mathbf{F}^{\mathrm{H}}\bar{\mathbf{x}} + \mathbf{F}\mathbf{w} = \mathbf{D}(\mathbf{h}_{\mathrm{F}})(\bar{\mathbf{P}}\bar{\mathbf{s}} + \bar{\mathbf{t}}) + \bar{\mathbf{w}}, \tag{10}$$

where $\mathbf{H}_c$ is an $N \times N$ column-wise circulant matrix with first column $[\mathbf{h}^{\mathrm{T}}\,\mathbf{0}^{\mathrm{T}}]^{\mathrm{T}}$, where $\mathbf{h}$ denotes a time-domain channel vector of length L, and $\mathbf{0}$ is an $(N-L) \times 1$ zero vector. In (10), $\mathbf{D}(\mathbf{h}_{\mathrm{F}})$ is an $N \times N$ diagonal channel matrix with principal diagonal components that are the elements of $\mathbf{h}_{\mathrm{F}}$, which is the frequency response of $\mathbf{h}$, and $\bar{\mathbf{w}} = \mathbf{F}\mathbf{w}$ with $\sigma_{\bar{\mathrm{w}}}^2 = \sigma_{\mathrm{w}}^2$.

Note that the novelty of the proposed scheme lies in constructing both a new linear precoder and a hidden pilot, both of which are well-suited for VLC applications. Unlike the previous study of an HP scheme [19], this approach considers VLC constraints, such as real-valued and unipolar OFDM modulated symbols for wireless optical transmission, and a dc-bias to control the dimming level for illumination functionality. The newly designed linear precoder and hidden pilot are then used to estimate the channel information and detect the signal transmitted from the LED lighting source.

IV. Channel Estimation and Symbol Detection

In practical VLC-OFDM systems, communication should be analyzed in the presence of a channel prediction error. In this section, a minimum mean square error (MMSE) channel estimator for HP-VLC is presented. At the receiver, the channel state information can be estimated by post-processing the received optical signal using the properties of the designed precoder and the hidden pilot. For this purpose, we define $\bar{\mathbf{B}}$, which is an $N \times L$ column-wise circulant matrix with $\bar{\mathbf{b}}$ as its first column. By multiplying $\bar{\mathbf{B}}^{\mathrm{H}}$ by (9), the received optical signal can be expressed as

$$\begin{aligned}\mathbf{z} &= \bar{\mathbf{B}}^{\mathrm{H}}\mathbf{k} = \bar{\mathbf{B}}^{\mathrm{H}}\mathbf{H}_c\bar{\mathbf{b}} + \bar{\mathbf{B}}^{\mathrm{H}}\mathbf{H}_c\bar{\mathbf{A}}\bar{\mathbf{s}} + \bar{\mathbf{B}}^{\mathrm{H}}\mathbf{w} \\ &= \bar{\mathbf{B}}^{\mathrm{H}}\bar{\mathbf{B}}\mathbf{h} + \mathbf{v} + \bar{\mathbf{B}}^{\mathrm{H}}\mathbf{w}.\end{aligned} \tag{11}$$

Because $\mathbf{H}_c$ is a circulant matrix, the commutative property of the circular convolution results in $\mathbf{H}_c\bar{\mathbf{b}} = \bar{\mathbf{B}}\mathbf{h}$. From (11), it is clear that $\mathbf{v} = \bar{\mathbf{B}}^{\mathrm{H}}\mathbf{H}_c\bar{\mathbf{A}}\bar{\mathbf{s}}$ becomes data interference, degrading the performance of the channel estimation. For accurate symbol detection, it is desirable to reduce $\mathbf{v}$. Here, we define $\bar{\mathbf{A}}_i$ as an $N \times L$ column-wise circulant matrix with $\bar{\mathbf{a}}_i$ as its first column, which is the ith column of $\bar{\mathbf{A}}$. Based on the property of the commutativity of the circular convolution, $\mathbf{H}_c\bar{\mathbf{A}} = [\mathbf{H}_c\bar{\mathbf{a}}_1, \mathbf{H}_c\bar{\mathbf{a}}_2, \ldots, \mathbf{H}_c\bar{\mathbf{a}}_{2M}]$ can be converted to $\mathbf{H}_c\bar{\mathbf{A}} = [\bar{\mathbf{A}}_1\mathbf{h}, \bar{\mathbf{A}}_2\mathbf{h}, \ldots, \bar{\mathbf{A}}_{2M}\mathbf{h}]$. Owing to the periodic cross-correlation property of the designed precoder and hidden pilot, both $\bar{\mathbf{B}}^{\mathrm{H}}\bar{\mathbf{A}}_i\mathbf{h}$ and the interference vector $\mathbf{v}$ decrease; hence, the channel can be identified successfully. Applying the MMSE criterion to (11), the channel estimate can be expressed as

$$\begin{aligned}\hat{\mathbf{h}} &= \mathbf{R}_{\mathbf{hz}}\mathbf{R}_{\mathbf{z}}^{-1}\mathbf{z} \\ &= \mathbf{R}_{\mathbf{h}}\bar{\mathbf{B}}^{\mathrm{H}}\bar{\mathbf{B}}\left(\bar{\mathbf{B}}^{\mathrm{H}}\bar{\mathbf{B}}\mathbf{R}_{\mathbf{h}}\bar{\mathbf{B}}^{\mathrm{H}}\bar{\mathbf{B}} + \mathbf{R}_{\mathbf{v}} + (\sigma_{\mathbf{w}}^2/N)\bar{\mathbf{B}}^{\mathrm{H}}\bar{\mathbf{B}}\right)^{-1}\mathbf{z}.\end{aligned} \tag{12}$$

To perform symbol detection given the result of the channel estimation, the interference caused by the hidden pilot vector should be removed. By subtracting $\mathbf{D}(\hat{\mathbf{h}}_{\mathrm{F}})\bar{\mathbf{t}}$, where $\mathbf{D}(\hat{\mathbf{h}}_{\mathrm{F}})$ is a diagonal matrix with a main diagonal of $\hat{\mathbf{h}}_{\mathrm{F}}$, which is an estimate of the frequency-domain channel $\mathbf{h}_{\mathrm{F}}$, in (10), a received symbol having a reduced pilot interference effect can be obtained, which can be expressed as

$$\bar{\mathbf{r}} = \mathbf{r} - \mathbf{D}(\hat{\mathbf{h}}_{\mathrm{F}})\bar{\mathbf{t}} = \mathbf{D}(\hat{\mathbf{h}}_{\mathrm{F}})\bar{\mathbf{P}}\bar{\mathbf{s}} + \boldsymbol{\varphi}, \tag{13}$$

where

$$\boldsymbol{\varphi} = \mathbf{D}(\tilde{\mathbf{h}}_{\mathrm{F}})(\bar{\mathbf{P}}\bar{\mathbf{s}} + \bar{\mathbf{t}}) + \bar{\mathbf{w}}. \tag{14}$$

Here, $\mathbf{D}(\tilde{\mathbf{h}}_{\mathrm{F}})$ denotes a diagonal matrix with a main diagonal of $\tilde{\mathbf{h}}_{\mathrm{F}} = \mathbf{h}_{\mathrm{F}} - \hat{\mathbf{h}}_{\mathrm{F}}$. Given that $\boldsymbol{\theta} = \mathbf{D}(\hat{\mathbf{h}}_{\mathrm{F}})\bar{\mathbf{P}}$, data detection using a linear MMSE is presented as

$$\bar{\mathbf{s}}_{\mathrm{mmse}} = \frac{P_s}{N}\boldsymbol{\theta}^{\mathrm{H}}\left(\frac{P_s}{N}\boldsymbol{\theta}\boldsymbol{\theta}^{\mathrm{H}} + \mathbf{R}_{\boldsymbol{\varphi}}\right)^{-1}\bar{\mathbf{r}}. \tag{15}$$

V. Illumination Quality Assessment

Because VLC is a communication technology based on LED lighting, it should meet the requirements of general illumination as a viable lighting source. Because noticeable illumination changes caused by flickering of a VLC signal are undesirable, a careful implementation considering the illumination task as a light source is required. Changes in the driving current used to run an LED circuit can cause changes to the chromaticity of the LED. Therefore, it is desirable to minimize the flickering range of an OFDM-based VLC signal to reduce the chromaticity changes caused by the fluctuation of a signal. As mentioned before, one of the main advantages of the proposed HP-VLC scheme is that it can reduce the flickering range of an OFDM-based VLC signal. To verify the advantages of the proposed HP-VLC scheme, metrics to measure the amount of flicker of a given signal are introduced.

The flicker index and percent flicker are examples of metrics that are commonly used to quantify the perceivable lighting quality [14]–[15]. The flicker index is a measure of the variation in output of a light source considering the waveform of the light output. Percent flicker is a relative measure of the cyclic variation in the output of a light source. This particular metric can be expressed as $100(U_1 - U_2)/(U_1 + U_2)$, where U_1 is the maximum and U_2 is the minimum output. As the percent flicker decreases, flicker becomes less noticeable to the human eye. In this paper, the percent flicker was chosen as a metric to measure the amount of flicker.

VI. Simulation Results

This section presents the simulation results of VLC OFDM signals under various average optical power and dynamic optical range constraints. The HP-VLC over DCO-OFDM was validated by computer simulations. The normalized power loaded to a hidden pilot was set to 0.5. In the simulations, the

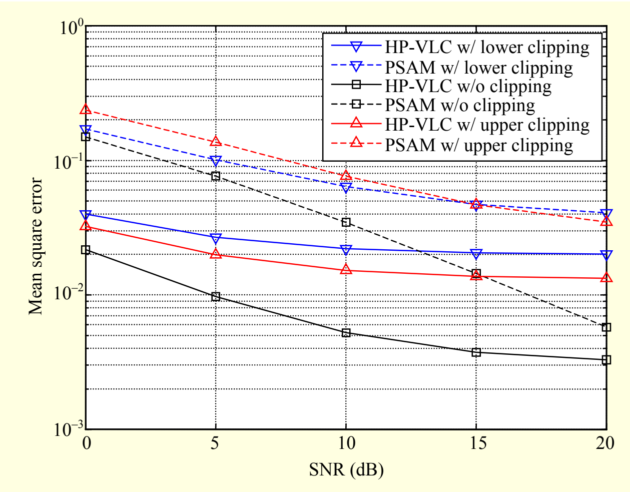

Fig. 3. Comparison of channel estimation error according to SNR.

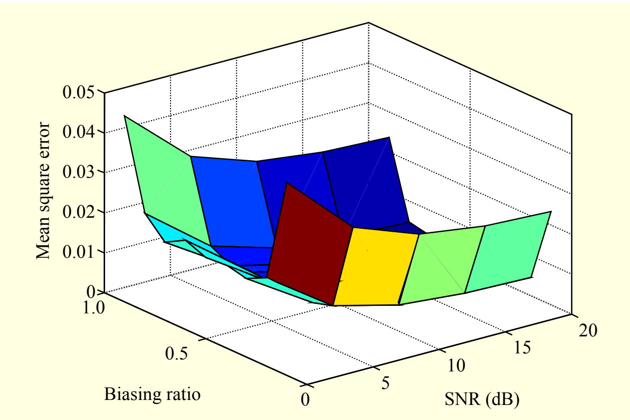

Fig. 4. Channel estimation error with respect to biasing ratio and SNR.

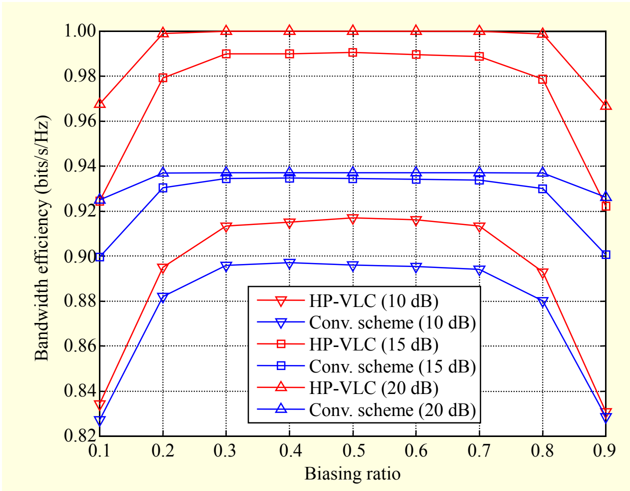

Fig. 5. Comparison of bandwidth efficiency according to biasing ratio.

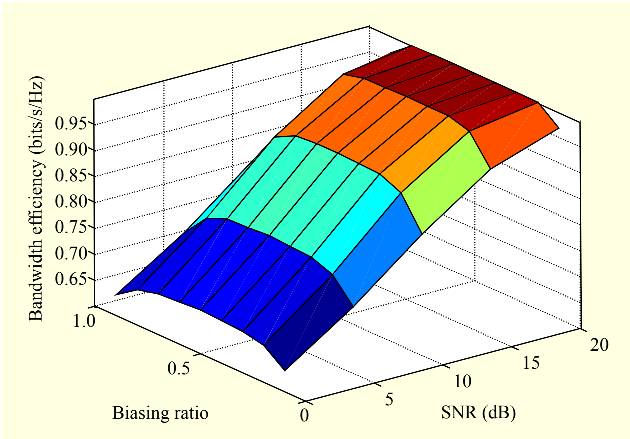

Fig. 6. Bandwidth efficiency with respect to biasing ratio and SNR.

number of subcarriers was $N = 256$, and QPSK was used for data modulation. A diffused multipath channel with tap length $L = 8$ was considered. To compare the channel estimation performance, PSAM was considered for a conventional OFDM-based VLC scheme.

Figure 3 compares the performance of the channel estimation according to SNR with dynamic range constraints. This figure shows that the HP-VLC gives the better performance over all SNR regions. Furthermore, when clipping takes place due to the limited dynamic range, the proposed HP-VLC is able to estimate the channel more accurately than the conventional PSAM. Because the proposed scheme exploits pilot symbols that are placed throughout all of the subcarriers, it overcomes the problems caused by symbol distortion on several subcarriers. Figure 4 shows the channel estimation performance according to biasing ratio and SNR. The channel estimation error is smallest when the biasing ratio is 0.5; this is because the clipping is minimized. On the other hand, when the biasing ratio approaches 0 or 1, a degraded performance is shown due to a loss in amplitude of the optical signal by clipping; thus, accurate channel estimation becomes difficult.

The bandwidth efficiency according to a changing biasing ratio is depicted in Fig. 5. The bandwidth efficiency increases when the biasing ratio approaches 0.5, due to the minimal effect of clipping. In addition, for the given different values of SNR, the proposed HP-VLC outperforms the conventional scheme. As the SNR increases, the performance gap between the two methods widens. The proposed scheme at a high SNR shows a 6.4% gain in bandwidth efficiency compared to the PSAM-based conventional method. Figure 6 shows the bandwidth efficiency with respect to biasing ratio and SNR. The best bandwidth-efficiency performance of HP-VLC is obtained when the biasing ratio is 0.5 and SNR is high.

Figure 7 shows the total clipping amplitude according to the biasing ratio. The maximum and minimum values of the total clipping amplitude are shown when the biasing ratio approaches 0.1 or 0.9 and 0.5, respectively. For various biasing ratio values, the clipping amplitude of the proposed scheme is always smaller than that of the conventional one. This is because a certain amount of power is loaded to the hidden pilot; hence, the variation of the OFDM signal amplitude becomes small in the case of the proposed HP-VLC scheme. Figure 8 compares the percent flicker of the proposed and conventional techniques for comparing the illumination quality. The proposed HP-VLC shows a lower percent flicker than that of the conventional approach. Recall that the flicker of an LED lamp is less detectable at a lower percent flicker. When the biasing ratio is greater than 0.3, the flickering of LED light presented using the proposed scheme becomes less noticeable to the human eye. In particular, the percent flicker of the proposed scheme can be lowered by 4% compared to that of the conventional one at a moderate level of dimming. Therefore, the proposed scheme will result in lower illumination degradation, such as fewer chromaticity changes.

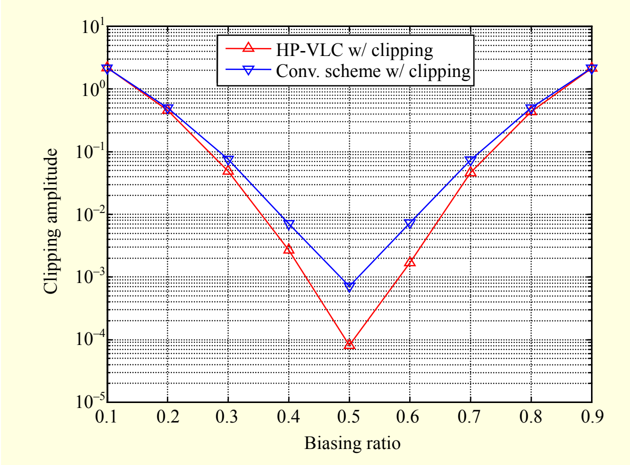

Fig. 7. Amount of total clipping amplitude according to biasing ratio.

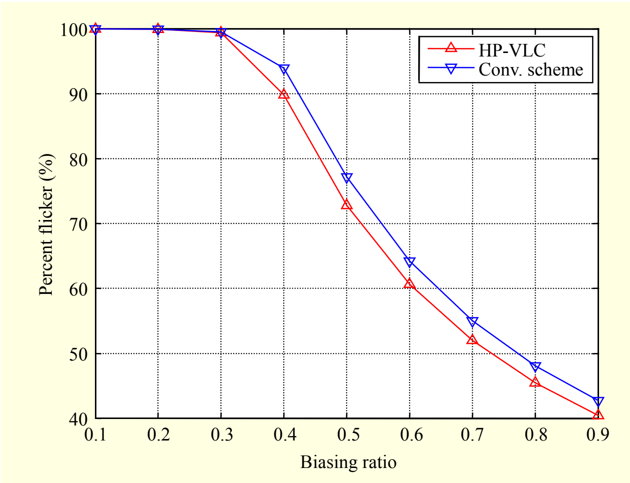

Fig. 8. Comparison of percent flicker according to biasing ratio.

VII. Conclusion

This paper proposed and demonstrated experimentally a hidden-pilot-aided precoding scheme for visible light communication (VLC). The novel designs of our precoder and hidden pilot enable OFDM-based VLC signals to avoid a significant loss in bandwidth efficiency and large fluctuations of LED light intensity. The simulation results confirmed that the bandwidth efficiency of the proposed scheme is approximately 6.4% larger than that of the conventional PSAM-based scheme due to the use of a spectrally efficient channel estimator. In addition, this approach can reduce the

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percent flicker by 4% compared to the conventional method; hence, the proposed scheme can enhance the flickering performance and stable behavior of LED lighting.

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