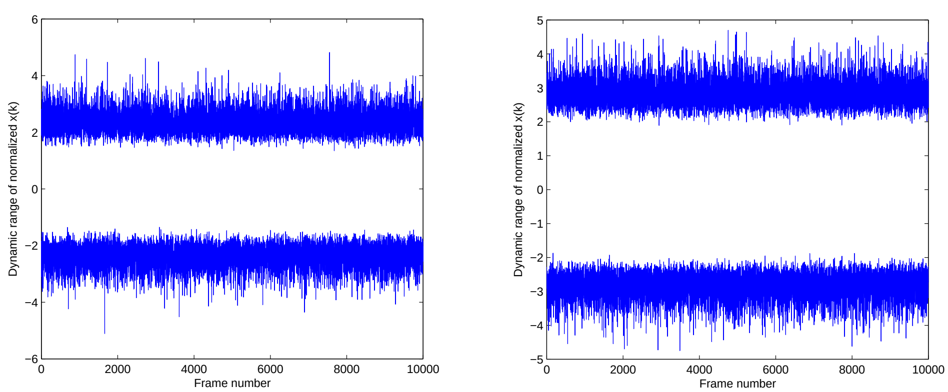
in comparison to the shot-noise and thermal-noise at the receiver. But the effective electronic power at the receiver is also small given a small α, hence the overall effective electronic SNR at the receiver becomes low. By contrast, increasing the scaling factor increases the effective electronic power at the receiver, but it also results in a signal, which is more likely to be outside the linear range of the LEDs, which in turn increases the clipping-distortion. Therefore, striking a compromise between the effective electronic power and the clipping-distortion is necessary, when choosing appropriate values for the scaling and biasing factors, in order to maximize the effective electronic SNR and to achieve good BER performance.

3. Proposed scheme

In current OFDM-based VLC systems [5], the "optimal" fixed scaling and biasing factors are found by minimizing the BER, which is equivalent to choosing the fixed scaling and biasing factors that maximize the average effective electronic SNR, and the scaling and biasing factors remain unchanged throughout the entire transmission period. However, the signal distributions are different for individual OFDM symbols according to Eq. (2). More specifically, for an OFDM-based VLC system relying on M-QAM and N subcarriers, the OFDM symbol assumes one of $M^{N/2-1}$ possible signals

$$\mathbb{X} = \left\{\mathbf{x}^{(l)}\right\}_{l=1}^{M^{N/2-1}}. \tag{8}$$

Figure 2 shows the dynamic range of $x(k)$ in 10000 OFDM symbols with $M = 16$ and $N = 64$ as well as $M = 64$ and $N = 256$, where the average electronic power of $x(k)$ is normalized. The dynamic range of $x(k)$ varies for different OFDM symbols and hence using constant scaling and biasing factors cannot fully exploit the linear range of LEDs, hence imposing a performance degradation.



(a) $M = 16, N = 64$

(b) $M = 64, N = 256$

Fig. 2. The dynamic range of the time-domain signal $x(k)$ in an OFDM-based VLC system with M-QAM and N subcarriers.

An exhaustive search could be carried out to find the optimal scaling and biasing factors $\alpha^{(l)}$ and $x_{bias}^{(l)}$ for the individual signal states $\mathbf{x}^{(l)} \in \mathbb{X}$ by maximizing the individual effective electronic SNRs

$$\Gamma_{b(elec)}^{(l)} = \frac{P_s^{(l)}}{\left(\sigma_{clip}^{(l)}\right)^2 + \sigma_{AWGN}^2}, \tag{9}$$

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where $P_s^{(l)}$ and $\left(\sigma_{clip}^{(l)}\right)^2$ denote the effective electronic power and the clipping-distortion power for the signal state $\mathbf{x}^{(l)}$, respectively. When the OFDM symbol takes the value of $\mathbf{x}^{(l)}$, the corresponding scaling and biasing factors $\alpha^{(l)}$ and $x_{bias}^{(l)}$ are applied. Such an exhaustive search would indeed, find the true optimal solution but its computational complexity may become prohibitive, since the size of the signal state set $M^{N/2-1}$ is typically excessive.

Our proposed adaptive scaling and biasing scheme is computationally much simpler and it calculates near-optimal scaling and biasing factors for each OFDM symbol according to the distribution of the time-domain OFDM signals. In particular, the scaling factor is chosen to strike a compromise between the effective electronic power and the clipping-distortion power, while the biasing factor is determined by minimizing the clipping-distortion, given the selected scaling factor. In the following, the calculation of the scaling and biasing factors is detailed.

3.1. Scaling factor calculation

For a time-domain OFDM symbol $\{x(k), k = 0, 1, \cdots, N-1\}$, let us denote the maximum and minimum of the symbol by $x_{\max}$ and $x_{\min}$, respectively. If the symbol is linearly transformed from $[x_{\min},\ x_{\max}]$ to $[z_{\min},\ z_{\max}]$, i.e. the scaling factor is given by

$$\alpha_{\min} = \frac{z_{\max} - z_{\min}}{x_{\max} - x_{\min}} \tag{10}$$

and the corresponding biasing factor is $x_{bias} = z_{\min} - \alpha_{\min} x_{\min}$, the transformed signals fully exploit the linear range of LEDs and no clipping is needed at the transmitter. In other words, the clipping-distortion power becomes zero. However, the effective electronic power is also small. On the other hand, if we inclrease the scaling factor, the effective electronic power is increased, but the clipping-distortion power is also increased. Instead of performing a complicated optimization to find the optimal scaling factor that strikes the optimal trade off between the effective electronic power and the clipping-distortion power, for implementational convenience, we simply set the scaling factor to

$$\alpha = \frac{2\left(z_{\max} - z_{\min}\right)}{x_{\max} + x_{\text{smax}} - x_{\min} - x_{\text{smin}}}, \tag{11}$$

where x_{smax} and x_{smin} represents the second largest and second smallest signals of $\{x(k), k = 0, 1, \cdots, N-1\}$, respectively. In general, the choice of α in Eq. (11) is not optimal. Heuristically, we can justify that this choice strikes a good compromise between the effective electronic power and the clipping-distortion power, yielding a near-optimal result. Clearly, this α value is larger than that given in Eq. (10) and, therefore, it yields a higher effective electronic power. On the other hand, this α value is not too large and, consequently, only a few signals with large absolute value are clipped. Thus, the clipping-distortion power is kept small. This may result in a favorable near-optimal effective electronic SNR.

Using Eq. (5) and noting that $X(0) = X(N/2) = 0$, we have

$$\begin{aligned}
\frac{1}{N}\sum_{k=0}^{N-1}\left(\alpha x(k) + x_{bias}\right) =& \frac{\alpha}{N^{3/2}}\sum_{k=0}^{N-1}\sum_{m=0}^{N-1} X(m)\exp\left(\frac{j2\pi mk}{N}\right) + x_{bias} \\
=& \frac{\alpha}{N^{3/2}}\sum_{m=0}^{N-1} X(m)\sum_{k=0}^{N-1}\exp\left(\frac{j2\pi mk}{N}\right) + x_{bias} \\
=& x_{bias},
\end{aligned} \tag{12}$$

which shows that the scaling factor does not change the optical power of the unclipped signal. Although the pilot in the OFDM symbol is scaled at the transmitter, the receiver does not need

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any knowledge about the scaling factor. This is because the scaling factor can be considered as part of the scaled channel state information (CSI), and the channel estimator at the receiver estimates this scaled CSI for equalization. Thus, no extra operation is required at the receiver.

3.2. Biasing factor calculation

The biasing factor only affects the clipping-distortion and makes no contribution to the effective electronic power. Therefore, the selection of the biasing factor is based on minimizing the clipping-distortion power for the given scaling factor, and the optimal biasing factor is expressed as

$$\hat{x}_{bias} = \arg \min_{x_{bias} \in \mathbb{R}^+} \sum_{k=0}^{N-1} f\left(\alpha x(k) + x_{bias}\right), \tag{13}$$

where $f(x)$ denotes the power of the clipping-distortion for each time-domain symbol, defined by

$$f(x) = \begin{cases} (x - z_{\max})^2, & x > z_{\max}; \\ 0, & z_{\min} \le x \le z_{\max}; \\ (x - z_{\min})^2, & x < z_{\min}. \end{cases} \tag{14}$$

The optimization problem in Eq. (13) can be solved by numerical algorithms, such as Newton's methods [13]. However, the complexity associated with a numerical optimization algorithm can be high, especially because the number of subcarriers used in an OFDM-based VLC system is usually large. Note that given the chosen scaling factor in Eq. (11), only a few signals with a large absolute value are clipped at the transmitter. Therefore, we may consider simply the maximum and minimum of $\{x(k), k = 0, 1, \cdots, N-1\}$ to directly derive a near-optimal biasing factor for solving the optimization of Eq. (13) as

$$\hat{x}_{bias} \approx (z_{\min} + z_{\max})/2 - \alpha\left(x_{\max} + x_{\min}\right)/2. \tag{15}$$

As discussed in Section 2, the bias only affects the $0th$ subcarrier, which is not used to carry the information. After the FFT operation at the receiver, the biasing factor is automatically removed. Therefore, the receiver does not have to know the biasing factor and no extra operation is needed at the receiver.

3.3. Computational complexity

As detailed in the previous two subsections, the proposed adaptive scaling and biasing scheme does not impose any extra operation at the receiver. Let us now summarize the computational requirements of this adaptive scheme at the transmitter. For the time-domain OFDM symbol $\{x(k), k = 0, 1, \cdots, N-1\}$ to be transmitted, our adaptive scaling and biasing scheme first finds the largest, second largest, smallest and second smallest signals, $x_{\max}$, x_{smax}, $x_{\min}$ and x_{smin}, of $\{x(k), k = 0, 1, \cdots, N-1\}$. which involves a modest computational complexity. The calculation of the scaling factor of Eq. (11) requires just one multiplication and three additions, as $2(z_{\max} - z_{\min})$ is a known value, while the calculation of the biasing factor of Eq. (15) needs only two multiplications and two additions, since $(z_{\min} + z_{\max})/2$ is a known value too. Clearly, this adaptive scaling and biasing scheme has an extremely low complexity.

3.4. Implementation issues

Practical implementations of OFDM-based VLC systems have been reported in [5, 6]. In our proposed scheme, the receiver remains unaltered. For the transmitter of Fig. 1, only the scaling

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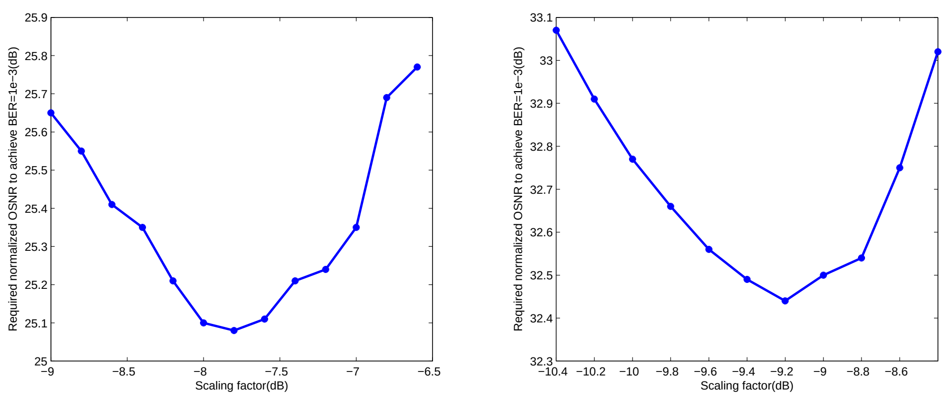
and biasing modules have to be slightly modified according to our method. To elaborate a little further, the adaptive scaling and biasing factor may be calculated with the aid of Eq. (11) and Eq. (15), which may be readily implemented using either field programmable gate arrays (FPGA) or digital signal processors (DSP). Furthermore, the adaptive scaling module can be realized by adjusting the gain of the power amplifier, while the adaptive biasing module relies on adjusting the current of the driver. Therefore, our proposed scheme has a convenient low-complexity implementation.

4. Simulation results

The BER performance of the proposed adaptive scaling and biasing scheme was evaluated by simulation, in comparison to the conventional OFDM-based VLC system [5]. The bandwidth of the LEDs was set to 100 MHz, and the linear range of the LEDs after pre-distortion was 0-160 mA [5]. Two different modulation schemes were used, namely, 16QAM with 64 subcarriers and 64QAM with 256 subcarriers, yielding the overall transmission rates of 387.5 Mbps and 595 Mbps, respectively. In the conventional OFDM-based VLC system, the biasing factor was set to the middle of the linear range of the LEDs, i.e. $x_{bias} = 80$ mA [5]. The standard deviation of $x(k)$ was assumed to be 80 mA. The target BER was set to 10^{-3}, which was within the error correction capability range of the conventional forward error correction (FEC) codes, such as convolutional codes, turbo codes or low density parity check codes [14].

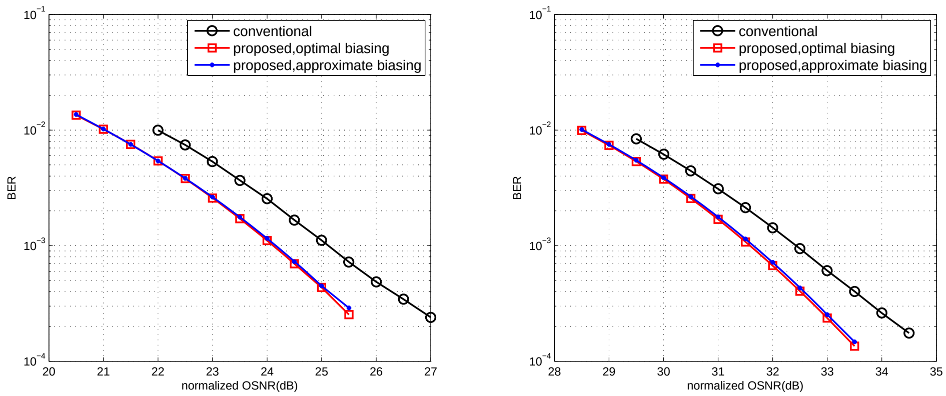
The single fixed scaling factor used for the conventional OFDM-based VLC system was determined by minimizing the required average normalized optical SNR (OSNR) to attain the required BER level of 10^{-3}, which was the ratio of the normalized emitted optical power to the electronic noise power at the receiver. The normalized OSNR values required for achieving the BER level of 10^{-3} for the two different modulation schemes are illustrated in Fig. 3. The fixed optimal scaling factors were -7.8 dB and -9.2 dB for the two cases, respectively, which were employed by the corresponding conventional OFDM-based VLC benchmark systems.



(a) $M = 16$, $N = 64$ (b) $M = 64$, $N = 256$

Fig. 3. The required normalized OSNR to achieve the BER level of 10^{-3} as the function of scaling factor for the conventional OFDM-based VLC system with M-QAM and N subcarriers.

Figure 4 compares the BER performance of our OFDM-based VLC system employing the proposed adaptive scaling and biasing scheme to that of the conventional system using the optimal fixed scaling factor indicated in Fig. 3. In our proposed scheme, the scaling factor



(a) $M = 16, N = 64$ (b) $M = 64, N = 256$

Fig. 4. The BER performance comparison of the conventional OFDM-based VLC system and our system with the proposed adaptive scaling and biasing scheme. The both systems employ M-QAM with N subcarriers.

was calculated by Eq. (11) for each OFDM symbol, while the biasing factor was either directly obtained by Eq. (15) (denoted as approximate biasing) or calculated by solving the optimization of Eq. (13) using a numerical algorithm (denoted as optimal biasing). It can be clearly seen from Fig. 4 that our adaptive system outperformed the conventional optimal system by about 1 dB in terms of the OSNR. It can also be seen that the proposed adaptive scheme using the approximate biasing factor of Eq. (15) attained almost the same performance as the proposed adaptive scheme with the optimal biasing factor. Therefore, the low-complexity approximation in Eq. (15) is deemed sufficiently accurate.

5. Conclusions

A low-complexity adaptive scaling and biasing scheme has been proposed for OFDM-based VLC systems, which fully exploits the dynamic range of LEDs and is capable of significantly improving the attainable system performance, while imposing an extremely low computational complexity at the transmitter and requiring no additional operation at the receiver. In our adaptive scheme, near-optimal scaling and biasing factors are calculated for each specific OFDM symbol according to the distribution of the signals with a few multiplications and additions, which strikes a beneficial compromise between the effective electronic power and the clipping-distortion power. Our simulation results have shown that the proposed adaptive system outperforms the current OFDM-based VLC system that employs the fixed optimal scaling and biasing factors over the entire transmission period.

Acknowledgments

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