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# Multiuser Transmit Precoding Design for Dimming Compatible Visible Light Communications

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**Abstract:** In multiuser visible light communication (VLC) systems, many transmit precoding (TPC) techniques have been investigated to suppress multiuser interference. However, these conventional works restrict their modulation to the special case of zero mean, which inherently limits their application to some popular modulations associated with the non-zero mean in VLC, such as pulse position modulation (PPM). Since the modulation with non-zero mean leads to more intricate optical power constraints and design objective functions than the case of zero mean, the TPC design that can support a general modulation is still an open problem. In the paper, we conceive of a general solution of the TPC scheme combined with dimming control for multiuser VLC systems, which is capable of mitigating multiuser interference, while at the same time, achieving the desired dimming level. The proposed scheme is applicable to a wide range of modulations in VLC, such as pulse amplitude modulation (PAM), PPM, and so on. Simulation results demonstrate that the proposed scheme outperforms the traditional pseudo-inverse-based zero-forcing TPC in terms of bit error rate (BER).

**Keywords:** light-emitting diode (LED); visible light communication (VLC); multiuser interference; transmit precoding

## 1. Introduction

Light-emitting diodes (LED) are expected to replace the traditional lighting sources and become the dominant device for illumination owing to their long lifetime and high power efficiency [1,2]. As a further benefit, the light of LEDs can be modulated to convey high-speed information data, leading to the concept of visible light communication (VLC) [3,4]. Superior to radio frequency (RF) communication, VLC possesses the advantages of operating in the unlicensed spectrum, whilst maintaining a high grade of information security, low cost, high data rate, etc. [5]. Thanks to these compelling advantages, VLC has found favor in various application scenarios, especially in indoor environments. Given the urgent customer demand for high-speed data transmission juxtaposed with the saturation of the radio frequency (RF) spectrum, VLC is deemed to be a promising candidate in the provision of ubiquitous indoor wireless communication [6,7].

In a typical indoor environment, multiple light-emitting diode (LED) sources are installed to provide sufficient indoor illumination, which can also be readily exploited for offering wireless services to multiple users [8,9]. Since the user terminals can detect light rays from multiple LEDs, inter-user interference arises, which may severely degrade the system performance if it is not carefully handled. In a multiuser scenario, transmit precoding (TPC) is an effective technique to suppress inter-user interference and improve attainable link performance [10]. The TPC techniques have been extensively studied in RF communications. However, these algorithms cannot be directly applied to VLC due to some specific features of VLC. More specifically, the LED-based indoor lighting infrastructure of VLC is used for simultaneously providing both illumination and communications [11]. Therefore, dimming control is critical and of high priority in practical applications in order to maintain the target illumination level [12,13]. Furthermore, in the context of intensity modulation and direct detection (IM/DD), the signal transmitted by LEDs is restricted to be non-negative [14]. Both distinctive features have inspired us to develop specific signal processing algorithms for the multiuser VLC system.

Recently, there have been several contributions to the multiuser TPC in VLC [15–21]. The authors of [15–18] investigated the zero-forcing (ZF) TPC strategies under various design criteria for multiuser VLC systems. In particular, [18] also included an optimal TPC scheme under the max-min fairness criterion. In [19], two kinds of linear precoding schemes were developed for coordinated VLC broadcasting architecture with the objective of minimizing the sum mean-squared error (MSE) given an illumination level and retaining a required performance at the minimal illumination level, respectively. Instead of employing the MSE criterion, the work in [20] proposed the optimal TPC design that maximizes the achievable sum rate of multiuser VLC systems. A recent work [21] considered a leakage-based TPC in VLC to suppress inter-user interference. All the above exciting contributions focused on TPC design using zero-mean modulation in VLC. Note that since the zero-mean modulation does not affect the average optical power, these works can be extended for supporting dimming control by directly adjusting the direct current (DC) bias. However, these works are not applicable to modulation schemes associated with the non-zero mean. This inherently limits their applications, since some modulation schemes like pulse position modulation (PPM) and on-off keying (OOK) are popular in VLC, but have the non-zero mean. Numerous challenges emerge in the multiuser TPC design when using the general modulations with the non-zero mean since these modulations will lead to more complicated optical power constraints, as well as a more intractable design objective function than the special case of zero-mean modulation. To the best of our knowledge, there is no general solution to the multiuser TPC design combined with dimming control in VLC.

Against this background, we propose a general solution of joint dimming control and multiuser TPC design in VLC, for mitigating the multiuser interference while maintaining a specific indoor illumination level. The main contributions of the paper are summarized as follows:

1. Instead of being restricted to the special case of zero-mean modulation, our scheme is capable of supporting a wide range of modulation schemes in VLC, such as pulse amplitude modulation (PAM) and PPM with a positive mean.
2. In contrast to RF communication, VLC is developed from the LED-based indoor lighting infrastructure. Therefore, several practical optical constraints including the LED non-linearity and illumination requirements are considered in our design for ensuring the normal operation of LEDs, as well as achieving the desired dimming level.
3. The optimal TPC subject to these practical constraints are developed with the objective of maximizing the minimum signal-to-interference-plus-noise ratio (SINR) among users. The proposed scheme exhibits a significant performance gain compared to the traditional pseudo-inverse-based ZF TPC.

To facilitate the reader, we here summarize the following notations used throughout the paper. Boldface upper case and boldface lower case letters represent matrices and column vectors, respectively. Furthermore, $\mathbf{I}_N$ is the identity matrix of size $N$, and $\mathbf{e}_i$ denotes the all-zero vector with a single one in the $i^{\text{th}}$ element. $||\cdot||_2$ denotes the $l_2$ norm of a vector. The operators $\text{vec}(\cdot)$ and $(\cdot)^T$ represent the vectorization and transpose of a matrix, respectively. The statistical expectation is denoted by $\text{E}\{\cdot\}$. The operator $\mathbf{A} \otimes \mathbf{B}$ is the Kronecker product of matrices $\mathbf{A}$ and $\mathbf{B}$.

## 2. System Model and Optical Power Constraints

### 2.1. Multiuser VLC Systems

We consider a multiuser VLC system composed of $N_t$ LED transmitters on the ceiling and $N_r$ user terminals, each equipped with an photodetector (PD) on the receiver plane, as shown in Figure 1. Let $\mathbf{s} = [s_1, \cdots, s_j \cdots, s_{N_r}]^T$ denote the real finite-magnitude symbol vector of all users, where $s_j$ represents the symbol transmitted to the $j^{\text{th}}$ user. The previous works required that $s_j$ be symmetrically bounded and have a zero mean, which restricts the modulation scheme to a very limited option, such as bipolar PAM, as Figure 2 depicts. This inherently limits their applications in VLC since some popular modulation schemes like PPM in Figure 2 cannot satisfy these strict requirements. In this paper, we consider a more general modulation scheme, with $s_j$ bounded by:

$$\Delta_{L,j} \le s_j \le \Delta_{H,j}, \quad (1)$$

where $\Delta_{L,j}$ and $\Delta_{H,j}$ are known modulation-dependent values. Furthermore, let $b_j$ and $u_j$ respectively denote the mean and the average power of $s_j$, i.e., $b_j = \mathrm{E}\{s_j\}$ and $u_j = \mathrm{E}\{s_j^2\}$.

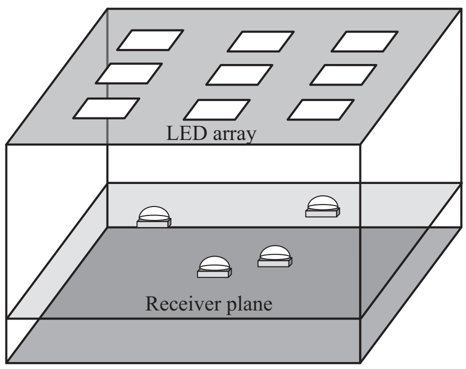


**Figure 1.** Multiuser VLC systems.

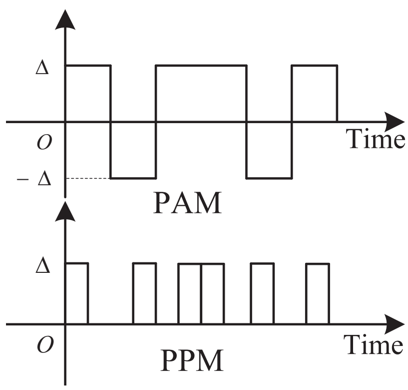


**Figure 2.** Pulse amplitude modulation (PAM) and pulse position modulation (PPM) waveforms.

In order to mitigate the multiuser interference, TPC is employed by exploiting the channel state information (CSI). Then, a suitable DC bias is added for producing positive signals. Consequently, the signals transmitted by the LED arrays can be expressed as:

$$\mathbf{x} = \mathbf{P}\mathbf{s} + \mathbf{d} = \sum_{j=1}^{N_r} \mathbf{p}_j s_j + \mathbf{d}, \quad (2)$$

Here, $\mathbf{P} \in \mathbb{R}^{N_t \times N_r}$ is the TPC matrix, $\mathbf{p}_j$ is the $j^{\text{th}}$ column of $\mathbf{P}$, which denotes the TPC vector of the $j^{\text{th}}$ user, and $\mathbf{d} = [d_1, \cdots, d_{N_t}]^{\text{T}}$ is the DC bias vector. Furthermore, the signal $x_i$ transmitted by the $i^{\text{th}}$ LED is given by:

$$x_i = \sum_{j=1}^{N_r} p_{ij} s_j + d_i, \tag{3}$$

where $p_{ij}$ is the $(i, j)^{\text{th}}$ element of $\mathbf{P}$.

At the receiver, the light rays detected by the PD are converted into electrical signals. After removing the DC bias, the received signal of the $k^{\text{th}}$ user is formulated as:

$$y_k = \mathbf{h}_k^T \mathbf{P} \mathbf{s} + n_k = \mathbf{h}_k^T \mathbf{p}_k s_k + \sum_{j \neq k} \mathbf{h}_k^T \mathbf{p}_j s_j + n_k, \tag{4}$$

where $\mathbf{h}_k$ is the channel matrix spanning from the LED array to the $k^{\text{th}}$ user and $n_k$ is the additive white Gaussian noise (AWGN) having a variance of $\sigma_k^2$. The received SINR of the $k^{\text{th}}$ user is expressed as:

$$\begin{aligned} \text{SINR}_k &= \frac{\text{E}\left[(\mathbf{h}_k^T \mathbf{p}_k s_k)^2\right]}{\text{E}\left[\left(\sum_{j \neq k} \mathbf{h}_k^T \mathbf{p}_j s_j + n_k\right)^2\right]} \\ &= \frac{u_k (\mathbf{h}_k^T \mathbf{p}_k)^2}{\sum_{j \neq k} \left[ u_j \left(\mathbf{h}_k^T \mathbf{p}_j\right)^2 + \underbrace{\sum_{i \neq k, j} b_i b_j \mathbf{h}_k^T \mathbf{p}_i \mathbf{h}_k^T \mathbf{p}_j}_{*} \right] + \sigma_k^2}, \end{aligned} \tag{5}$$

where $b_j$ and $u_j$, respectively, denote the mean and the average power of $s_j$, i.e., $b_j = \text{E}\{s_j\}$ and $u_j = \text{E}\{s_j^2\}$. The SINR is a ubiquitous metric used for evaluating the communication performance, which will also be adopted as the design criterion in the paper. Note that the term $*$ exists due to the general modulation with non-zero mean. This is markedly different from the case of zero-mean modulation and makes the TPC design more intractable.

### 2.2. Optical Constraints

In VLC, LEDs are the main source of non-linearity. Due to the LED non-linearity, the signal transmitted by the $i^{\text{th}}$ LED is constrained to a limited linear dynamic range, i.e., $d_{L,i} \leq x_i \leq d_{H,i}$, where $d_{L,i}$ and $d_{H,i}$ denote the minimum and maximum drive current permitted by the $i^{\text{th}}$ LED, respectively [22]. Next, we will derive the specific optical constraints imposed on the design to ensure that the signals transmitted by LEDs operate within their limited linear dynamic range. Let us first define $\Delta_j = \frac{\Delta_{H,j} - \Delta_{L,j}}{2}$ and $c_j = \frac{\Delta_{H,j} + \Delta_{L,j}}{2}$. Since we have:

$$|s_j - c_j| \leq \Delta_j, \tag{6}$$

where $| \cdot |$ denotes the absolute value operator, it follows that:

$$|\sum_{j=1}^{N_r} p_{ij}(s_j - c_j)| \leq \sum_{j=1}^{N_r} |p_{ij}||s_j - c_j| \leq \sum_{j=1}^{N_r} |p_{ij}|\Delta_j. \tag{7}$$

Equivalently, it yields:

$$-\sum_{j=1}^{N_r} |p_{ij}|\Delta_j \leq \sum_{j=1}^{N_r} p_{ij}(s_j - c_j) \leq \sum_{j=1}^{N_r} |p_{ij}|\Delta_j. \tag{8}$$

By rearranging the above inequalities and introducing $d_i$ in the inequalities, we have:

$$-\sum_{j=1}^{N_r}|p_{ij}|\Delta_j+\sum_{j=1}^{N_r}p_{ij}c_j+d_i\leq\sum_{j=1}^{N_r}p_{ij}s_j+d_i\leq\sum_{j=1}^{N_r}|p_{ij}|\Delta_j+\sum_{j=1}^{N_r}p_{ij}c_j+d_i. \tag{9}$$

Based on the expression of $x_i$ in (3), we can formulate the dynamic range of $x_i$ in the following matrix form:

$$-\operatorname{abs}\{\mathbf{e}_i^T\mathbf{P}\}\boldsymbol{\Delta}+\mathbf{e}_i^T\mathbf{P}\mathbf{c}+d_i\leq x_i\leq\operatorname{abs}\{\mathbf{e}_i^T\mathbf{P}\}\boldsymbol{\Delta}+\mathbf{e}_i^T\mathbf{P}\mathbf{c}+d_i, \tag{10}$$

where the above formulation stems from the fact that:

$$\begin{cases}\operatorname{abs}\{\mathbf{e}_i^T\mathbf{P}\}\boldsymbol{\Delta}=\sum_{j=1}^{N_r}|p_{ij}|\Delta_j,\\ \mathbf{e}_i^T\mathbf{P}\mathbf{c}=\sum_{j=1}^{N_r}p_{ij}c_j,\\ \mathbf{e}_i=\begin{bmatrix}\mathbf{0}_{1\times(i-1)} & 1 & \mathbf{0}_{1\times(N_r-i-1)}\end{bmatrix}^T.\end{cases} \tag{11}$$

Here, $\mathbf{e}_i$ denotes the $i^{\text{th}}$ standard basis vector for the $N_r$-dimensional space, $(\cdot)^T$ represents the transpose operator, $\operatorname{abs}\{\cdot\}$ is the element-wise absolute value operator, $\mathbf{0}_{1\times n}$ is an all-zero row-vector of size $n$, $\boldsymbol{\Delta}=[\Delta_1,\cdots,\Delta_{N_r}]^T$, and $\mathbf{c}=[c_1,\cdots,c_{N_r}]^T$. To ensure that $d_{L,i}\leq x_i\leq d_{H,i}$, $\mathbf{p}_i$ and $d_i$ should satisfy:

$$\begin{cases}-\operatorname{abs}\{\mathbf{e}_i^T\mathbf{P}\}\boldsymbol{\Delta}+\mathbf{e}_i^T\mathbf{P}\mathbf{c}+d_i\geq d_{L,i},\\ \operatorname{abs}\{\mathbf{e}_i^T\mathbf{P}\}\boldsymbol{\Delta}+\mathbf{e}_i^T\mathbf{P}\mathbf{c}+d_i\leq d_{H,i}.\end{cases} \tag{12}$$

Consequently, in order to guarantee that all LEDs operate within their limited linear dynamic range, the following optical constraints are imposed:

$$\begin{cases}\operatorname{abs}\{\mathbf{P}\}\boldsymbol{\Delta}-\mathbf{P}\mathbf{c}\leq\mathbf{d}-\mathbf{d}_L\\ \operatorname{abs}\{\mathbf{P}\}\boldsymbol{\Delta}+\mathbf{P}\mathbf{c}\leq\mathbf{d}_H-\mathbf{d}\end{cases}, \tag{13}$$

where $\mathbf{d}_L=[d_{L,1},\cdots,d_{L,N_t}]^T$ and $\mathbf{d}_H=[d_{H,1},\cdots,d_{H,N_t}]^T$.

### *2.3. Dimming Control*

In VLC, the main functionalities of LEDs are to provide first indoor illumination and then communications. Since people are insensitive to fluctuations of light signals as long as the frequency of modulation is above 100 Hz, but only perceive the average optical intensity of LEDs, the average optical power should remain constant over time to provide stable brightness. Given the linear relationship between the radiated optical power and drive current, the constraint imposed on the signal $x_i$ of the $i^{\text{th}}$ LED to achieve the stable brightness is given by:

$$\begin{aligned}\mathrm{E}\{x_i\}&=\mathrm{E}\left\{\sum_{j=1}^{N_r}p_{ij}s_j+d_i\right\}=\sum_{j=1}^{N_r}p_{ij}\mathrm{E}\left\{s_j\right\}+d_i\\&=\sum_{j=1}^{N_r}p_{ij}b_j+d_i=d_{t,i},\ i=1,2,\cdots,N_t,\end{aligned} \tag{14}$$

where $d_{t,i}$ is the average amplitude of the drive current required for the target dimming level. Equivalently, the illumination requirement of (14) for all $N_t$ LEDs takes the concentrated form of:

$$\mathrm{E}\{\mathbf{x}\}=\mathbf{P}\mathbf{b}+\mathbf{d}=\mathbf{d}_t, \tag{15}$$

where $\mathbf{b} = [b_1, \cdots, b_{N_r}]^T$ and $\mathbf{d}_t = [d_{t,1}, \cdots, d_{t,N_t}]^T$. From (15), one can observe that both $\mathbf{P}$ and $\mathbf{d}$ need to be designed to achieve the target dimming level. Since the dimming level of the $i^{\text{th}}$ LED is defined as $\eta = (d_{t,i} - d_{L,i})/(d_{H,i} - d_{L,i})$, the average amplitude of the drive current for a dimming level $\eta_t$ can be set to:

$$d_{t,i} = d_{L,i} + (d_{H,i} - d_{L,i})\eta. \tag{16}$$

where $\eta$ is in general between zero and one.

## 3. Joint Multiuser TPC Design and Dimming Control

In this section, we propose a joint TPC design and dimming control scheme under the constraints of LED non-linearity and indoor illumination for the multiuser VLC systems. The objective of our design is to maximize the minimum SINR among users, as well as to achieve a desired dimming level. Accordingly, we can formulate our design as the following optimization problem:

$$\begin{aligned} \max_{\mathbf{P},\mathbf{d}} \ & \min_{k=1,\cdots,N_r} \ \text{SINR}_k, \\ \text{s.t.} \ & \text{abs}\{\mathbf{P}\}\boldsymbol{\Delta} - \mathbf{P}\mathbf{c} \leq \mathbf{d} - \mathbf{d}_L, \\ & \text{abs}\{\mathbf{P}\}\boldsymbol{\Delta} + \mathbf{P}\mathbf{c} \leq \mathbf{d}_H - \mathbf{d}, \ \mathbf{P}\mathbf{b} + \mathbf{d} = \mathbf{d}_t, \end{aligned} \tag{17}$$

where $\text{SINR}_k$ is calculated according to (5). Explicitly, in the above problem, both $\mathbf{P}$ and $\mathbf{d}$ are jointly optimized. By reformulating the dimming constraint in (15), we have:

$$\mathbf{d} = \mathbf{d}_t - \mathbf{P}\mathbf{b}. \tag{18}$$

Thus, the optimization problem in (17) can be equivalently simplified to:

$$\begin{aligned} \max_{\mathbf{P}} \ & \min_{k=1,\cdots,N_r} \ \text{SINR}_k, \\ \text{s.t.} \ & \text{abs}\{\mathbf{P}\}\boldsymbol{\Delta} - \mathbf{P}\widehat{\mathbf{c}} \leq \widehat{\mathbf{d}}_L, \ \text{abs}\{\mathbf{P}\}\boldsymbol{\Delta} + \mathbf{P}\widehat{\mathbf{c}} \leq \widehat{\mathbf{d}}_H, \end{aligned} \tag{19}$$

where $\widehat{\mathbf{c}} = \mathbf{c} - \mathbf{b}$, $\widehat{\mathbf{d}}_L = \mathbf{d}_t - \mathbf{d}_L$ and $\widehat{\mathbf{d}}_H = \mathbf{d}_H - \mathbf{d}_t$. It is observed that the above optimization problem is non-convex with respect to (w.r.t.) $\mathbf{P}$, which is difficult to solve. Next, we will equivalently transform the problem into a more tractable form and obtain the optimal solution by invoking the bisection methods. Let us introduce $\mathbf{p} = \text{vec}(\mathbf{P})$. Then, we have:

$$\begin{aligned} & \text{abs}\{\mathbf{P}\}\boldsymbol{\Delta} = \text{vec}(\text{abs}\{\mathbf{P}\}\boldsymbol{\Delta}) = (\boldsymbol{\Delta}^T \otimes \mathbf{I}_{N_t})\text{abs}\{\mathbf{p}\}, \\ & \mathbf{P}\widehat{\mathbf{c}} = \text{vec}(\mathbf{P}\widehat{\mathbf{c}}) = (\widehat{\mathbf{c}}^T \otimes \mathbf{I}_{N_t})\mathbf{p}. \end{aligned} \tag{20}$$

Thus, the constraints of (19) can be reformulated as:

$$\widetilde{\boldsymbol{\Delta}}\text{abs}\{\mathbf{p}\} - \mathbf{C}\mathbf{p} \leq \widehat{\mathbf{d}}_L, \ \widetilde{\boldsymbol{\Delta}}\text{abs}\{\mathbf{p}\} + \mathbf{C}\mathbf{p} \leq \widehat{\mathbf{d}}_H, \tag{21}$$

where $\widetilde{\boldsymbol{\Delta}} = \boldsymbol{\Delta}^T \otimes \mathbf{I}_{N_t}$ and $\mathbf{C} = \widehat{\mathbf{c}}^T \otimes \mathbf{I}_{N_t}$. Then, by introducing the slack variable $\mathbf{f}$ [19], we can transform the constraints to the following equivalent linear formulations:

$$\widetilde{\boldsymbol{\Delta}}\mathbf{f} - \mathbf{C}\mathbf{p} \leq \widehat{\mathbf{d}}_L, \ \widetilde{\boldsymbol{\Delta}}\mathbf{f} + \mathbf{C}\mathbf{p} \leq \widehat{\mathbf{d}}_H, \ -\mathbf{f} \leq \mathbf{p} \leq \mathbf{f}. \tag{22}$$

Furthermore, given a non-negative value $\gamma$, $\text{SINR}_k \geq \gamma$ leads to:

$$\sum_{j \neq k} \left[ u_j \left( \mathbf{h}_k^T \mathbf{p}_j \right)^2 + \sum_{i \neq k,j} b_i b_j \mathbf{h}_k^T \mathbf{p}_i \mathbf{h}_k^T \mathbf{p}_j \right] + \sigma_k^2 \leq \frac{u_k}{\gamma} \left( \mathbf{h}_k^T \mathbf{p}_k \right)^2. \tag{23}$$

Rewriting the second item on the left-hand side of (23) yields the equivalent expression of:

$$
\begin{aligned}
\sum_{j\neq k}\sum_{i\neq k,j} b_i b_j \mathbf{h}_k^T\mathbf{p}_i\mathbf{h}_k^T\mathbf{p}_j &= \left(\sum_{j\neq k} b_j\mathbf{h}_k^T\mathbf{p}_j\right)^2 - \sum_{j\neq k} b_j^2\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2 \\
&= \left(\sum_{j} b_j\mathbf{h}_k^T\mathbf{p}_j - b_k\mathbf{h}_k^T\mathbf{p}_k\right)^2 - \sum_{j\neq k} b_j^2\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2 \\
&= \left(\mathbf{h}_k^T\sum_{j} b_j\mathbf{p}_j - b_k\mathbf{h}_k^T\mathbf{p}_k\right)^2 - \sum_{j\neq k} b_j^2\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2.
\end{aligned} \tag{24}
$$

Since we have:

$$
\mathbf{Pb} = [\mathbf{p}_1, \mathbf{p}_2, \cdots, \mathbf{p}_{N_r}]\,\mathbf{b} = \sum_j b_j\mathbf{p}_j, \tag{25}
$$

(24) can be further expressed as:

$$
\sum_{j\neq k}\sum_{i\neq k,j} b_i b_j \mathbf{h}_k^T\mathbf{p}_i\mathbf{h}_k^T\mathbf{p}_j = \left(\mathbf{h}_k^T\mathbf{Pb} - b_k\mathbf{h}_k^T\mathbf{p}_k\right)^2 - \sum_{j\neq k} b_j^2\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2. \tag{26}
$$

Additionally, since we have:

$$
\begin{aligned}
\sum_{j\neq k} b_j^2\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2 &= \sum_{j} b_j^2\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2 - b_k^2\left(\mathbf{h}_k^T\mathbf{p}_k\right)^2, \\
\sum_{j\neq k} u_j\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2 &= \sum_{j} u_j\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2 - u_k\left(\mathbf{h}_k^T\mathbf{p}_k\right)^2,
\end{aligned} \tag{27}
$$

the left-hand side of (23) can be equivalently rewritten as:

$$
\begin{aligned}
&\sum_{j\neq k}\left[u_j\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2 + \sum_{i\neq k,j} b_i b_j\mathbf{h}_k^T\mathbf{p}_i\mathbf{h}_k^T\mathbf{p}_j\right] + \sigma_k^2 \\
&= \sum_j u_j\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2 - u_k\left(\mathbf{h}_k^T\mathbf{p}_k\right)^2 + \left(\mathbf{h}_k^T\mathbf{Pb} - b_k\mathbf{h}_k^T\mathbf{p}_k\right)^2 - \sum_j b_j^2\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2 + b_k^2\left(\mathbf{h}_k^T\mathbf{p}_k\right)^2 + \sigma_k^2 \\
&= \sum_{j=1}^{N_r}(u_j - b_j^2)\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2 + \left(\mathbf{h}_k^T\mathbf{Pb} - b_k\mathbf{h}_k^T\mathbf{p}_k\right)^2 + \sigma_k^2 - (u_k - b_k^2)\left(\mathbf{h}_k^T\mathbf{p}_k\right)^2.
\end{aligned} \tag{28}
$$

Thus, the inequality in (23) can be reformulated as:

$$
\begin{aligned}
&\sum_{j=1}^{N_r}(u_j - b_j^2)\left(\mathbf{h}_k^T\mathbf{p}_j\right)^2 + \left(\mathbf{h}_k^T\mathbf{Pb} - b_k\mathbf{h}_k^T\mathbf{p}_k\right)^2 + \sigma_k^2 \\
&\qquad \leq \frac{u_k}{\gamma}\left(\mathbf{h}_k^T\mathbf{p}_k\right)^2 + (u_k - b_k^2)\left(\mathbf{h}_k^T\mathbf{p}_k\right)^2.
\end{aligned} \tag{29}
$$

Using the equalities:

$$
\begin{aligned}
\mathbf{p}_i &= \mathrm{vec}(\mathbf{Pe}_i) = (\mathbf{e}_i^T\otimes\mathbf{I}_{N_t})\mathbf{p} \triangleq \mathbf{W}_i\mathbf{p}, \\
\mathbf{h}_k^T\mathbf{Pb} &= \mathrm{vec}\left(\mathbf{h}_k^T\mathbf{Pb}\right) = (\mathbf{b}^T\otimes\mathbf{h}_k^T)\mathbf{p},
\end{aligned} \tag{30}
$$

where $\mathbf{W}_i \triangleq \mathbf{e}_i^T\otimes\mathbf{I}_{N_t}$, (29) can be formulated in the form of $l_2$ norm, which is given by:

$$
||\mathbf{B}_k\mathbf{p} + \mathbf{v}_k||_2 \leq \varepsilon_k\mathbf{h}_k^T\mathbf{W}_k\mathbf{p}, \tag{31}
$$

where $\mathbf{B}_k$, $\mathbf{v}_k$, and $\varepsilon_k$ are defined as:

$$\mathbf{B}_k = \begin{bmatrix} \mathbf{h}_k^T \mathbf{W}_1 (u_1 - b_1^2) \\ \vdots \\ \mathbf{h}_{N_r}^T \mathbf{W}_{N_r} (u_{N_r} - b_{N_r}^2) \\ \mathbf{b}^T \otimes \mathbf{h}_k^T - b_k \mathbf{h}_k^T \mathbf{W}_k \\ \mathbf{0}_{1\times N_t N_r} \end{bmatrix}, \quad \mathbf{v}_k = \begin{bmatrix} 0, & \cdots, & 0, & \sigma_k, \end{bmatrix}^T, \quad \varepsilon_k = \sqrt{\frac{u_k}{\gamma} + (u_k - b_k^2)}, \tag{32}$$

where $\mathbf{0}_{1\times N_t N_r}$ is an all-zero row vector of size $N_t N_r$. Since the set defined by (31) is a second-order cone (SOC), the design problem of (19) is a quasi-convex problem [23]. In this case, the optimal solution of (19) can be efficiently obtained, e.g., by the bisection methods. Accordingly, the feasibility problem used to search for the optimal solution in the bisection methods is given by:

$$\begin{aligned} &\text{find } \mathbf{p}, \\ &\text{s.t. } ||\mathbf{B}_k \mathbf{p} + \mathbf{v}_k||_2 \le \varepsilon_k \mathbf{h}_k^T \mathbf{W}_k \mathbf{p},\ k = 1, \cdots, N_r, \\ &\quad \widetilde{\boldsymbol{\Delta}}\mathbf{f} - \mathbf{C}\mathbf{p} \le \widehat{\mathbf{d}}_L,\ \widetilde{\boldsymbol{\Delta}}\mathbf{f} + \mathbf{C}\mathbf{p} \le \widehat{\mathbf{d}}_H, \\ &\quad -\mathbf{f} \le \mathbf{p} \le \mathbf{f}. \end{aligned} \tag{33}$$

Note that the above problem is SOC programming, which can be efficiently solved by standard convex optimization methods, such as the interior-point method [23]. Finally, the procedure of the proposed joint TCP design and dimming control is summarized in Algorithm 1.

**Algorithm 1** Joint TPC design and dimming control.

1: Initialize $\gamma_{\min} = \gamma_1$ and $\gamma_{\max} = \gamma_2$, where $\gamma_1$ is sufficiently small so that (33) is feasible when $\gamma = \gamma_1$, and $\gamma_2$ is large enough so that (33) is feasible when $\gamma = \gamma_2$. Let $\rho > 0$ be the target precision.
2: **while** $\gamma_{\max} - \gamma_{\min} > \rho$ **do**
3: Set $\gamma = (\gamma_{\max} + \gamma_{\min})/2$.
4: Solve (33). If the problem is feasible, then set $\gamma_{\min} = \gamma$. Otherwise, set $\gamma_{\max} = \gamma$.
5: **end while**
6: The optimal TPC vector for the $k^{\text{th}}$ user is $\mathbf{p}_k^* = \mathbf{W}_k \mathbf{p}'$, where $\mathbf{p}'$ is the last feasible solution to (33). Then, the DC bias required for the desired dimming level can be obtained based on (18).

## 4. Numerical Results and Discussion

In this section, our numerical results are presented for evaluating the performance of the proposed TPC combined with dimming control. The multiuser VLC system as shown in Figure 3 was comprised of nine LED arrays distributed uniformly on the ceiling to offer sufficient illumination [16]. We considered the scenarios of $N_r = 6$ (Scenario 1) and $N_r = 8$ (Scenario 2) users decentralized on the receiver plane, whose locations w.r.t. the LED arrays are presented in Figure 3. Two kinds of typical modulations in VLC were adopted in the simulation, namely bipolar PAM with zero mean and PPM with positive mean. The linear dynamic range of a single LED was set to $1 \sim 20$ mW. Other major parameters are listed in Table 1.

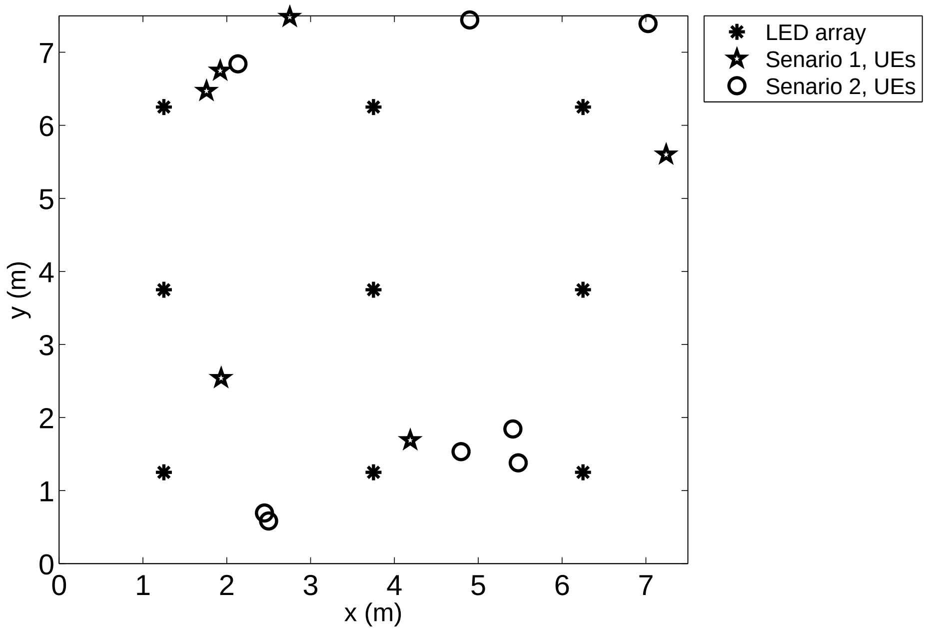


**Figure 3.** The room model. The room size was 7.5 m × 7.5 m × 3 m. The height of the receiver was 0.7 m from the floor. The height of LED arrays was 3 m from the floor [16].

**Table 1.** Parameters of the MU-MISOindoor VLC system.

| Parameter | Value |
|---|---|
| Number of LED arrays | 9 |
| Number of LEDs per array | 3600 (60 × 60) |
| LED pitch | 0.01 m |
| Size of LED array | 0.59 m × 0.59 m |
| Transmitter semi-angle | 70 deg. |
| Receiver FOV | 60 deg. |
| Detector responsivity | 0.53 A/W |
| Physical area of the detector | 1 cm$^2$ |
| Gain of optical filter | 1.0 |
| Refractive index | 1.5 |
| Bandwidth | 100 MHz |

Figure 4 illustrates the bit error rate (BER) of the proposed TPC scheme using PAM at different dimming levels, in which the BER of the traditional pseudo-inverse based ZF TPC from RF is also provided for comparison [24]. Observe in Figure 4 that for both scenarios, the proposed TPC achieved a significant BER performance gain compared to the ZF TPC. The BER performance became better when the dimming level tended towards 50%, since the linear dynamic range of LED can be fully exploited in this case. Additionally, the BER performance for Scenario 1 with six users was better than Scenario 2 with eight users, implying that the BER performance of the dimming compatible VLC system degraded when supporting more users. From Figure 4, we also observe that the performance of the multiuser VLC system degraded with the increasing PAM modulation order.

In Figure 5, we portray the BER of the multiuser VLC system employing 2-PPM and 4-PPM, which both have the non-zero mean. It can be observed from Figure 5 that our TPC scheme still achieved much better performance than the ZF TPC for PPM, which verifies the applicability of the proposed scheme to modulations with the non-zero mean. In contrast to PAM, a better performance was achieved when employing the higher-order PPM. This is because as the modulation order increased, the power efficiency of PPM was improved at the cost of its bandwidth efficiency deterioration [25]. Moreover, under relatively low or high dimming levels, the multiuser VLC system employing PAM exhibited a performance loss, while the TPC employing PPM performed well. PPM appeared to be a beneficial design choice to provide a stable communication link at relatively low or high dimming levels despite its low spectrum efficiency compared to PAM.

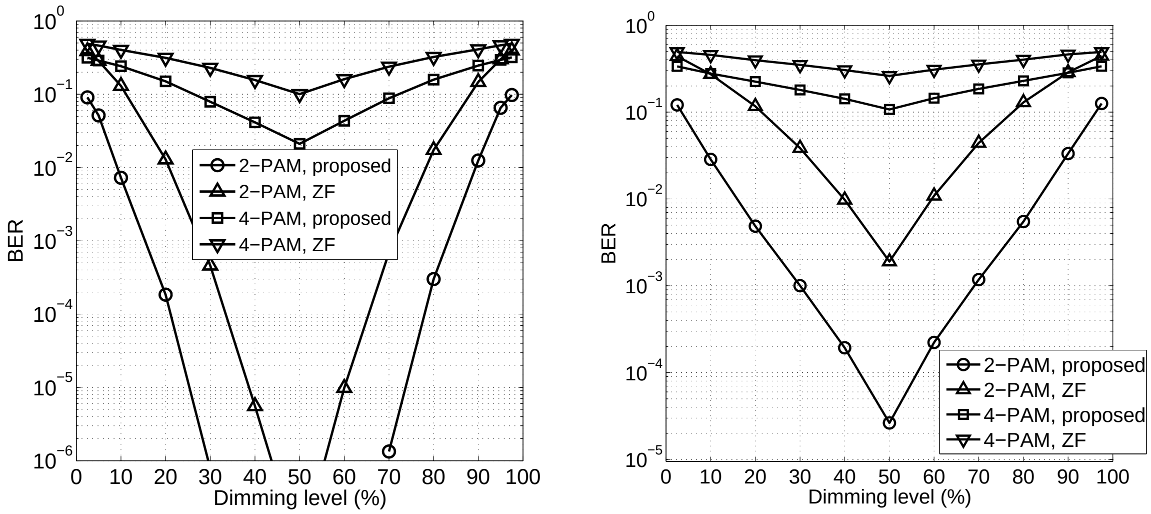


**Figure 4.** BER of the multiuser VLC system using PAM (left: Scenario 1, right: Scenario 2). ZF, zero-forcing.

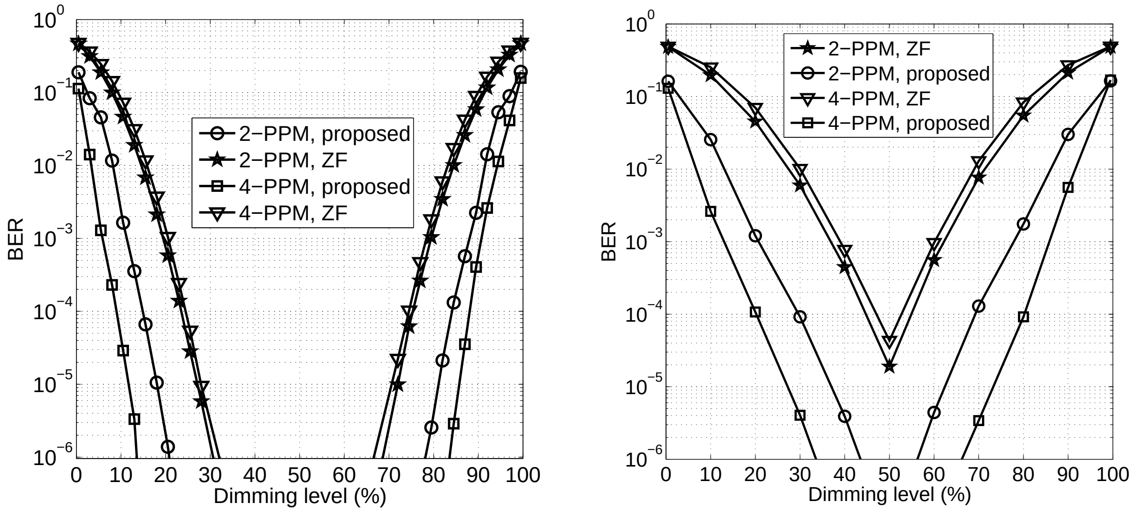


**Figure 5.** BER of the multiuser VLC system using PPM (left: Scenario 1, right: Scenario 2).

## 5. Conclusions

A novel TPC design combined with dimming control was developed for multiuser VLC systems, which is capable of suppressing multiuser interference, while at the same time achieving desired illumination requirements. Unlike the conventional methods, which are restricted to the modulation schemes associated with the zero mean, the proposed scheme is applicable to a wide range of modulation in VLC, such as PAM and PPM. Simulation results demonstrate that the proposed TPC outperformed the traditional pseudo-inverse-based ZF TPC transplanted from RF communication. Additionally, the VLC system employing PPM exhibited a better BER performance than PAM under relatively low or high dimming levels, implying that PPM is a beneficial design option at relatively low or high dimming levels.

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