Joint Precoder and DC Bias Design for MIMO VLC Systems

Yumin Zeng, Jiaheng Wang, Xintong Ling, Xiao Liang, Chunming Zhao
National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, China
Email: {ymzeng, jhwang, xtling, xiaoliang, cmzhao}@seu.edu.cn

***Abstract*—Visible light communication (VLC) can provide high-speed data transmission and meet the daily illumination demand simultaneously, and thus emerges as a promising technology for future indoor wireless communication. This paper proposes effective methods to jointly design the precoder and DC bias for multiple-input multiple-output (MIMO) VLC systems. The design goal is to minimize the mean square error (MSE) between the transmitted and received VLC signals. The non-negative constraint on the transmitted signal and two different power constraints are considered. We first consider the per-LED power constraint and propose an effective solution to the precoder design problem. Then, the proposed method is extended to address the similar joint precoder and bias design problem under the sum power constraint. Finally, the performance of the proposed precoder and DC bias designs is evaluated via simulations.**

***Index Terms*—DC bias, MIMO, per-LED power constraint, precoder, visible light communication (VLC).**

I. Introduction

Visible light communication (VLC) is able to support high-speed data transmission and provide daily illumination simultaneously [1], [2], and thus has received increasing attention in both the academic and industrial societies. VLC systems often use light-emitting diodes (LEDs) to transmit information and use photo diodes (PDs) or imaging sensors to detect light signals at the receiver. The advantages of VLC include low-cost, simple implementation, license-free spectrum, high security, safety and so on [3].

VLC systems can be embedded into the existing illumination infrastructure and commonly consist of multiple light sources. Multiple LEDs can be used to achieve spatial multiplexing and support high data rates with limited modulation bandwidth [4]. Another advantage of multiple LEDs is to provide flexibility for dimming control to meet the illumination requirement. Thus, it is natural to consider employing multiple-input multiple-output (MIMO) transmission in VLC systems [5]. Different from the conventional radio frequency communication (RFC) systems, the transmitted signals in VLC systems must to be real and non-negative [6], [7]. Hence, the existing MIMO transceiver designs cannot be directly applied to VLC MIMO systems, which thus calls for new transceiver designs [8], [9].

The power and offset allocation in a MIMO VLC system was studied in [8], where the precoder design was simplified into a power allocation problem. In [9], the authors studied the multi-color VLC beamformer and offset optimization problem under the sum power constraint and proposed a solution based on the water-filling method, which, however, was suboptimal. Note that in VLC systems, each LED usually has its own circuit and is individually driven. Therefore, it is more practical and reasonable to consider the per-LED power constraint [10]. However, the VLC MIMO precoder design under the per-LED power constraint has not been investigated yet.

In this paper, we consider a joint design of the precoder and DC bias for MIMO VLC systems under either the per-LED power constraint or the sum power constraint. The non-negativeness of the transmitted signal is also taken into account. We first address the precoder design problem under the per-LED power constraint and propose an efficient method to solve it. Then, utilizing the solution obtained in the case of the per-LED power constraint, we develop a novel method to address the joint precoder and bias design problem under the sum power constraint. The performance of the proposed designs is verified by simulation results.

The paper is organized as follows. In Section II, we describe the MIMO VLC system model, the channel model, the constraints and the joint precoder and DC bias design problems. In Section III, efficient methods are proposed to address the precoder and bias design problem under two different constraints, i.e., the per-LED and sum power constraints. Section IV provides the simulation results and the conclusion is presented in Section V.

Notation: We use uppercase and lowercase boldface letters to denote matrices and vectors, respectively. Notations $\mathbf{A}^{-1}$ and $\mathbf{A}^T$ represent the inverse and transpose of an matrix $\mathbf{A}$, respectively. The trace of the matrix $\mathbf{A}$ is denoted by $\mathrm{Tr}(\mathbf{A})$. $[\mathbf{A}]_{ij}$ denotes the (i-th, j-th) diagonal element of the matrix $\mathbf{A}$ and $\mathbb{E}(\cdot)$ represents the expectation operations. Finally, $\mathbf{I}_N$ represents an identity matrix of size $N \times N$.

II. System Model

A. Signal Model

We consider a point-to-point MIMO VLC system, as shown in Fig. 1, which consists of N LEDs at the transmitter and M PDs at the receiver. The bit stream is mapped onto the M-Pulse Amplitude Modulation (PAM) symbols, forming a symbol vector $\mathbf{s} = [s_1, s_2, ..., s_K]^T$, where s_k for $k = 1, 2, ..., K$ has a zero mean and is normalized such that $s_k \in [-1, 1]$. Let c denotes the covariance of s_k, i.e., $\mathbb{E}[s_k^2] = c$. The transmitted symbols are assumed to be independent of each other, i.e., $\mathbb{E}[\mathbf{s}\mathbf{s}^T] = c\mathbf{I}_K$.

The symbol vector $\mathbf{s}$ is firstly processed by a real precoding matrix and then a DC bias (vector) is added to guarantee the non-negativeness of the transmitted signal. The transmitted signal vector $\mathbf{x}$ is given by

$$\mathbf{x} = \mathbf{P}\mathbf{s} + \mathbf{b} \geq \mathbf{0} \tag{1}$$

where $\mathbf{P}$ is an $N \times K$ real precoding matrix and $\mathbf{b}$ is an $N \times 1$ positive DC bias vector.

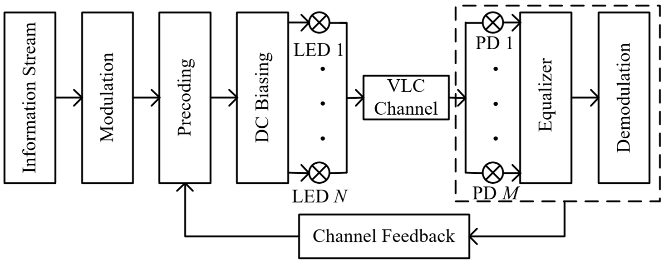

Figure 1: Schematic diagram of a MIMO VLC system.

The transmitted signals from various LEDs are spatially superimposed and detected by different PDs at the receiver. The received signal vector $\mathbf{y}$ can be expressed as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} = \mathbf{H}\mathbf{P}\mathbf{s} + \mathbf{H}\mathbf{b} + \mathbf{n} \tag{2}$$

where $\mathbf{H}$ is the channel matrix containing the channel response between the LEDs and PDs, and $\mathbf{n}$ is a combination of thermal noise and shot noise and obeys a zero-mean Gaussian distribution, i.e., $\mathbf{n} \sim \mathcal{N}(\mathbf{0}, \sigma_n^2 \mathbf{I}_M)$, where σ_n^2 is the noise variance corresponding to each detector.

The DC bias in the received signal vector, which corresponds to $\mathbf{Hb}$ in (2), is removed at the receiver, since it is added to guarantee the non-negativeness and does not contain any information. Consequently, the effective received signal $\bar{\mathbf{y}}$ is given by

$$\bar{\mathbf{y}} = \mathbf{H}\mathbf{P}\mathbf{s} + \mathbf{n}. \tag{3}$$

At the receiver, to recover the transmitted signal, we apply a minimum mean square error (MMSE) equalizer [11]

$$\mathbf{G}^T = \mathbf{P}^T\mathbf{H}^T(\sigma_n^2/c \cdot \mathbf{I} + \mathbf{H}\mathbf{P}\mathbf{P}^T\mathbf{H}^T)^{-1} \tag{4}$$

to the received signal $\bar{\mathbf{y}}$. The estimated transmitted signal vector $\hat{\mathbf{s}}$ is then given by

$$\hat{\mathbf{s}} = \mathbf{G}^T\bar{\mathbf{y}}. \tag{5}$$

B. VLC Channel Model

VLC channels vary slowly and can be modeled as baseband linear time-invariant channels [12], [13]. Different from the conventional RFC channels, VLC channels exhibit a low-pass property and are often regarded as static or semi-static. Thus, it is reasonable to assume that the receiver can estimate the channel state information (CSI) properly and feedback CSI to the transmitter.

A MIMO VLC channel includes VLC links between multiple LEDs and PDs. Each VLC link contains two components: the direct line of sight (LOS) component and the non-direct line of sight (NLOS) component [14], [15]. As revealed in [14], the LOS component contributes more than 95% of the optical power at the receiver and thus the NLOS component is negligible compared to the LOS component. For the sake of simplicity of model, we only consider the LOS component in the channel model below.

The MIMO VLC channel matrix $\mathbf{H}$ can be expressed as

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N} \\ h_{21} & h_{22} & \cdots & h_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ h_{M1} & h_{M2} & \cdots & h_{MN} \end{bmatrix} \tag{6}$$

where $h_{ij}(i = 1, 2, \ldots, M; j = 1, 2, \ldots, N)$ represents the channel attenuation between PD i and LED j, which can be formulated as [16]

$$h_{ij} = \frac{\rho A_e}{d_{ij}^2} \frac{(m+1)}{2\pi} (\cos\varphi)^m \tag{7}$$

where ρ is the detector responsivity, d_{ij} is the distance between PD i and LED j, m is related to the half power semi-angle $\phi_{1/2}$ via $m = -ln2/ln(cos(\phi_{1/2}))$, φ is the angle of irradiance and A_e is the effective receiving area given by

$$A_e = \begin{cases} A_{pd} n_r^2 \cos\psi / \sin^2 \psi_c & \psi \leq \psi_c \\ 0 & \psi > \psi_c \end{cases} \tag{8}$$

where A_{pd} is the area of received PD, n_r is the internal refractive index, ψ is the angle of incidence and ψ_c denotes the field-of-view (FOV) of the receiver.

C. The Non-negative and Per-LED Power Constraints

For VLC using LEDs, due to the intensity modulation, the transmitted signal must be non-negative, i.e.,

$$\mathbf{x} = \mathbf{P}\mathbf{s} + \mathbf{b} \geq \mathbf{0}. \tag{9}$$

However, such a constraint depends on the instantaneous transmitted symbol vector $\mathbf{s}$, and cannot be directly used in the precoding design. Since $s_k \in [-1, 1]$, to get rid of the dependence on the symbol vector, the non-negative constraint in (9) can be safely replaced by the following constraints:

$$\| \mathbf{e}_i^T \mathbf{P} \|_1 - \mathbf{e}_i^T \mathbf{b} \leq 0, \quad i = 1, ..., N \tag{10}$$

where $\| \cdot \|_1$ is the 1-norm and $\mathbf{e}_i$ is a selection vector, which is the (i-th) column of $\mathbf{I}_N$. The constraints in (10) ensure that for any symbol vector $\mathbf{s}$, the transmitted signal $\mathbf{x}$ must be non-negative.

The existing works on VLC MIMO transmission designs (e.g., [8] and [9]) considered the sum power constraint over all LEDs. However, in practice, it is more reasonable to set the power budget for each LED, since each LED has its own circuit and is individually driven. Thus, we introduce the per-LED power constraint into the VLC precoder design problem, which so far has not been investigated yet.

The transmitted signal for LED i is expressed as $\mathbf{x}_i = \mathbf{e}_i^T(\mathbf{P}\mathbf{s} + \mathbf{b})$ and thus the per-LED optical power budget can be written as

$$p_i = \mathbb{E}[\mathbf{e}_i^T(\mathbf{P}\mathbf{s} + \mathbf{b})] = \mathbf{e}_i^T\mathbf{P}\mathbb{E}[\mathbf{s}] + \mathbf{e}_i^T\mathbf{b} \tag{11}$$

where p_i is the power budget of LED i .

Note that s_k for $k = 1, 2, ..., K$ has a zero mean and thus the expectation of the symbol vector $\mathbf{s}$ is zero, i.e., $\mathbb{E}[\mathbf{s}] = \mathbf{0}$. Therefore, the per-LED power constraints can be expressed as

$$b_i \leq P_i, \forall i \tag{12}$$

where b_i is the DC bias for LED i and P_i is the power constraint for LED i.

D. Problem Statement

The mean square error (MSE) is a compelling performance metric that strikes a trade-off between the effects of the channel and noise, which is adopted in this paper. Since we apply an MMSE equalizer to recover the symbol vector, the associated error covariance matrix $\mathbf{R}$ can be derived as

$$\begin{aligned} \mathbf{R} &= \mathbb{E}[(\mathbf{s} - \hat{\mathbf{s}})(\mathbf{s} - \hat{\mathbf{s}})^T] \\ &= \sigma_n^2(\sigma^2\mathbf{I} + \mathbf{P}^T\mathbf{H}^T\mathbf{H}\mathbf{P})^{-1} \end{aligned} \tag{13}$$

where $\sigma^2 = \sigma_n^2/c$ is defined. Therefore, the sum MSE is given by

$$f(\mathbf{P}) = \mathrm{Tr}(\mathbf{R}) = \sigma_n^2\mathrm{Tr}[(\sigma^2\mathbf{I} + \mathbf{P}^T\mathbf{H}^T\mathbf{H}\mathbf{P})^{-1}]. \tag{14}$$

Then, the joint precoder and bias design of the MIMO VLC system under the non-negative and per-LED power constraints is formulated as

$$\begin{aligned} \min_{\mathbf{P},\mathbf{b}} \quad & \sigma_n^2\mathrm{Tr}[(\sigma^2\mathbf{I} + \mathbf{P}^T\mathbf{H}^T\mathbf{H}\mathbf{P})^{-1}] \\ \text{s.t.} \quad & \| \mathbf{e}_i^T\mathbf{P} \|_1 - b_i \leq 0 \\ & b_i \leq P_i, \forall i. \end{aligned} \tag{15}$$

Similarly, the joint precoder and bias design under the sum power constraint is formulated as

$$\begin{aligned} \min_{\mathbf{P},\mathbf{b}} \quad & \sigma_n^2\mathrm{Tr}[(\sigma^2\mathbf{I} + \mathbf{P}^T\mathbf{H}^T\mathbf{H}\mathbf{P})^{-1}] \\ \text{s.t.} \quad & \| \mathbf{e}_i^T\mathbf{P} \|_1 - b_i \leq 0 \\ & \sum_{i=1}^{N} b_i \leq P_{total} \end{aligned} \tag{16}$$

where P_{total} is the sum power constraint for all LEDs.

III. Joint Precoder and DC bias Design

A. Design Under the Per-LED Power Constraint

In this section, we propose an effective method to address problem (15). The main difficulty is the non-convexity of the objective. Thus we first convert the objective by introducing a new matrix $\mathbf{Q} = \mathbf{P}\mathbf{P}^T$, which is real and semi-definite. Using the relation [17]

$$\begin{aligned} &\mathrm{Tr}[(\mathbf{I}_N + \mathbf{M}_{N\times M}\mathbf{N}_{M\times N})^{-1}] \\ &= \mathrm{Tr}[(\mathbf{I}_M + \mathbf{N}_{M\times N}\mathbf{M}_{N\times M})^{-1}] + N - M, \end{aligned} \tag{17}$$

we can transform $f(\mathbf{P})$ as

$$\begin{aligned} f(\mathbf{P}) &= \sigma_n^2\mathrm{Tr}[(\sigma^2\mathbf{I} + \mathbf{P}^T\mathbf{H}^T\mathbf{H}\mathbf{P})^{-1}] \\ &= \sigma_n^2\mathrm{Tr}[(\sigma^2\mathbf{I} + \mathbf{H}\mathbf{P}\mathbf{P}^T\mathbf{H}^T)^{-1}] \\ &= \sigma_n^2\mathrm{Tr}[(\sigma^2\mathbf{I} + \mathbf{H}\mathbf{Q}\mathbf{H}^T)^{-1}] \\ &= g(\mathbf{Q}) \end{aligned} \tag{18}$$

where $M = N$ is assumed in this paper for simplicity, and the extension to the case of $M \neq N$ is straightforward. By such a transformation, we obtain a new objective function $g(\mathbf{Q})$ which is convex in $\mathbf{Q}$.

Furthermore, utilizing the relation $\|\mathbf{a}\|_1 \leq \sqrt{n}\|\mathbf{a}\|_2$, where $\mathbf{a}$ is an n-order vector [17], the non-negative constraints in (10) can be safely approximated by the following constraints:

$$N[\mathbf{Q}]_{ii} - b_i^2 \leq 0. \tag{19}$$

Thus, we try to solve the following problem which can be considered as a safe approximation of the original problem (15), as

$$\begin{aligned} \min_{\mathbf{Q}} \quad & \sigma_n^2\mathrm{Tr}[(\sigma^2\mathbf{I} + \mathbf{H}\mathbf{Q}\mathbf{H}^T)^{-1}] \\ \text{s.t.} \quad & N[\mathbf{Q}]_{ii} - P_i^2 \leq 0, \forall i. \end{aligned} \tag{20}$$

It is easily found that problem (20) is a convex problem. Therefore, we can obtain the precoder design via standard convex optimization tools, such as CVX [18] or SeDuMi [19].

B. Design Under the Sum Power Constraint

The solution to problem (15) can be extended to address the joint precoder and DC bias design problem under the sum power constraint, i.e., problem (16), where the per-LED power budget can be viewed as variables and further optimized. For this purpose, we firstly define the following matrix function:

$$\mathbf{U}(\mathbf{Q}) \triangleq (\sigma^2\mathbf{I} + \mathbf{H}\mathbf{Q}\mathbf{H}^T)^{-1}. \tag{21}$$

Then, problem (16) now can be written equivalently as

$$\begin{aligned} \min_{\mathbf{Q},\mathbf{t}} \quad & \sigma_n^2\mathrm{Tr}[\mathbf{U}(\mathbf{Q})] \\ \text{s.t.} \quad & N[\mathbf{Q}]_{ii} \leq t_i^2, \forall i \\ & \sum_{i=1}^{N} t_i \leq P_{total} \\ & t_i \geq 0, \forall i \end{aligned} \tag{22}$$

where $\mathbf{t} \triangleq [t_1, t_2, \ldots, t_N]^T$ and t_i is the power budget for LED i.

For fixed $\mathbf{t}$, the problem (22) is equivalent to problem (20) under the per-LED power constraint, which has been solved in the previous section. Now, the question is how to optimize the additional variables $\mathbf{t}$. For this purpose, we define the following function:

$$h(\mathbf{t}) \triangleq \sigma_n^2\mathrm{Tr}[\mathbf{U}(\mathbf{Q}^\star)] \tag{23}$$

where $\mathbf{Q}^\star$ is the optimal solution to (22) with given $\mathbf{t}$. We show that $h(\mathbf{t})$ has the following property.

Proposition 1. *Let $\mathbf{Q}^\star$ is the solution to the problem (22) for a given $\mathbf{t}$. Then, the partial derivative of $h(\mathbf{t})$ at t_i is*

$$\frac{\partial h(\mathbf{t})}{\partial t_i} = \begin{cases} \dfrac{2t_i\sigma_n^2}{N}[\mathbf{U}(\mathbf{Q}^\star) \cdot \mathbf{H}^T\mathbf{H} \cdot \mathbf{U}(\mathbf{Q}^\star)]_{ii}, & [\mathbf{Q}^\star]_{ii} = t_i \\ 0, & [\mathbf{Q}^\star]_{ii} \neq t_i. \end{cases} \tag{24}$$

Proof: The partial derivative of objective function is derived by $\partial h(\mathbf{t})/\partial t_i = \partial \mathcal{L}(\mathbf{Q}^\star, d_i^\star, t_i)/\partial t_i$ [20], where $d_i^\star$ denotes the optimal Lagrange multiplier associated with the constraints $[\mathbf{Q}]_{ii} \leq t_i^2/N$, and $\mathcal{L}(\mathbf{Q}, d_i, t_i)$ is the partial Lagrangian of problem (22) as

$$\mathcal{L}(\mathbf{Q}, d_i, t_i) = \sigma_n^2 \mathrm{Tr}[\mathbf{U}(\mathbf{Q})] + d_i(t_i^2/N - [\mathbf{Q}]_{ii}). \tag{25}$$

The partial derivative of $h(\mathbf{t})$ is derived as

$$\frac{\partial h(\mathbf{t})}{\partial t_i} = \partial \mathcal{L}(\mathbf{Q}^\star, d_i^\star, t_i)/\partial t_i = 2d_i^\star t_i/N. \tag{26}$$

Thus, we find the optimal Lagrange multiplier $d_i^\star$ to obtain $\partial h(\mathbf{t})/\partial t_i$. The KKT conditions of (22), which although are not sufficient due to the non-convexity, are the necessary optimality conditions and can be derived as

$$\begin{aligned} & d_i^\star(t_i^2/N - [\mathbf{Q}^\star]_{ii}) = 0 \\ & \frac{\partial \mathcal{L}(\mathbf{Q}^\star, d_i^\star, t_i)}{\partial [\mathbf{Q}^\star]_{ii}} = \frac{\partial\{\sigma_n^2 \mathrm{Tr}[\mathbf{U}(\mathbf{Q}^\star)]\}}{\partial [\mathbf{Q}^\star]_{ii}} - d_i^\star = 0. \end{aligned} \tag{27}$$

Since the $[\mathbf{Q}]_{ii}$ is the (i-th) diagonal element of $\mathbf{Q}$, we can obtain the following relation as [21]

$$\begin{aligned} & \frac{\partial\{\sigma_n^2 \mathrm{Tr}[\mathbf{U}(\mathbf{Q})]\}}{\partial [\mathbf{Q}]_{ii}} \\ & = \frac{\partial\{\sigma_n^2 \mathrm{Tr}[(\sigma^2 \mathbf{I} + \mathbf{H}\mathbf{Q}\mathbf{H}^T)^{-1}]\}}{\partial [\mathbf{Q}]_{ii}} \\ & = \sigma_n^2[(\sigma^2 \mathbf{I} + \mathbf{H}\mathbf{Q}\mathbf{H}^T)^{-1}\mathbf{H}^T\mathbf{H}(\sigma^2 \mathbf{I} + \mathbf{H}\mathbf{Q}\mathbf{H}^T)^{-1}]_{ii} \\ & = \sigma_n^2[\mathbf{U}(\mathbf{Q}) \cdot \mathbf{H}^T\mathbf{H} \cdot \mathbf{U}(\mathbf{Q})]_{ii}. \end{aligned} \tag{28}$$

Therefore, we obtain that $d_i^\star = 0$ if $[\mathbf{Q}^\star]_{ii} \neq t_i$, and $d_i^\star = \sigma_n^2[\mathbf{U}(\mathbf{Q}^\star) \cdot \mathbf{H}^T\mathbf{H} \cdot \mathbf{U}(\mathbf{Q}^\star)]_{ii}$ if $[\mathbf{Q}^\star]_{ii} = t_i$. Then, the partial derivative of $h(\mathbf{t})$ is given in (24) in Proposition 1. ■

Proposition 1 indicates that $h(\mathbf{t})$ is not only continuous but also differentiable. Therefore, we can obtain the gradient of $h(\mathbf{t})$ as $\mathbf{d}(\mathbf{t}) = [\partial h(\mathbf{t})/\partial t_1, \partial h(\mathbf{t})/\partial t_2, \ldots, \partial h(\mathbf{t})/\partial t_N]^T$, where $\partial h(\mathbf{t})/\partial t_i$ is the partial derivative derived in Proposition 1. We can make use of the gradient to propose a number of gradient-based methods [22] to solve problem (22). In particular, considering the constraints set

$$\mathcal{T} \triangleq \{\mathbf{t} : \sum_{i=1}^{N} t_i \leq P_{total},\, t_i \geq 0,\, \forall i\} \tag{29}$$

is a simplex, we propose a simple iterative algorithm that updates $\mathbf{t}$ as

$$\mathbf{t}(k+1) = [\mathbf{t}(k) + \tau(k)\mathbf{d}(\mathbf{t}(k))]_{\mathcal{T}} \tag{30}$$

where $\tau(k)$ is the step size of the algorithm and $[\cdot]_{\mathcal{T}}$ is the projection onto the set $\mathcal{T}$. This method has two advantages. First, it is easy to obtain the gradient $\mathbf{d}(\mathbf{t})$, as provided in Proposition 1. Second, the projection can be realized in a typical water-filling method. Indeed, if $\mathbf{t} = [\mathbf{z}]_{\mathcal{T}}$, then $t_i = [z_i - \theta]_+$ for $\forall i$, where the waterlevel θ is the minimum value such that $\sum_{i=1}^{N} t_i \leq P_{total}$. Such an algorithm is formally described in Algorithm 1.

Algorithm 1 extends the solution obtained in the case of the per-LED power constraint and addresses the precoder and DC bias design problem under the sum power constraint. It iteratively optimizes the system performance, while in each iteration, the sum power constraint is always satisfied. Therefore, Algorithm 1 can be used online. With properly chosen step size, it is guaranteed to converge to a locally optimal solution.

Algorithm 1 Joint Precoder and Bias Design

1. set the initial point $\mathbf{t}(0)$ and precision ε and let $k = 0$;
2. obtain the $\mathbf{Q}^\star$ based on $\mathbf{t}(k)$;
3. calculate the derivative $\partial h(\mathbf{t})/\partial t_i(k)$ for $\forall i$ with (24);
4. $\mathbf{d}(\mathbf{t}(k)) = [\partial h(\mathbf{t})/\partial t_1, \partial h(\mathbf{t})/\partial t_2, \ldots, \partial h(\mathbf{t})/\partial t_N]^T$;
5. $\mathbf{t}(k+1) = [\mathbf{t}(k) + \tau(k)\mathbf{d}(\mathbf{t}(k))]_{\mathcal{T}}$;
6. $k = k+1$, if $\|\mathbf{t}(k) - \mathbf{t}(k-1)\| > \varepsilon$, go to step 2.

IV. Simulation Results

In this section, we present simulation results to demonstrate the performance of the proposed precoder and DC bias designs. We consider a scenario with 4 LEDs at the transmitter and 4 PDs at the receiver. The simulation parameters of the MIMO VLC system are listed in Table I. Other parameters are chosen as $c = 1$ and $\sigma_n^2 = 10^{-5}$.

Table I : Simulation Parameters for VLC System Configuration.

Parameters	Values
Room size (m)	$5 \times 5 \times 3$
LED1 position (m)	[1.0, 1.0, 2.0]
LED2 position (m)	[3.0, 1.0, 2.0]
LED3 position (m)	[3.0, 3.0, 2.0]
LED4 position (m)	[1.0, 3.0, 2.0]
PD1 position (m)	[1.0, 1.0, 0.5]
PD2 position (m)	[1.1, 1.0, 0.5]
PD3 position (m)	[1.1, 1.1, 0.5]
PD4 position (m)	[1.0, 1.1, 0.5]
Transmitter semi-angle	60°
Detector responsivity (A/W)	0.53
PD area (cm^2)	1.0
Gain of optical filter	1.0
Refractive index	1.5
Receiver FOV	60°

Fig. 2 displays the iterative process of Algorithm 1. It can be observed that Algorithm 1 converges rapidly. It approaches the solution within 5 iterations and reaches the convergence point in about 50 iterations. In each iteration, Algorithm 1 requires to solve a convex problem, i.e., (20), and computes the gradient $\mathbf{d}(\mathbf{t})$ using Proposition 1. During the iterative process, Algorithm 1 always strictly complies with the sum power limit and thus can be used online.

In Fig. 3, we compare the proposed precoder and DC bias designs under the per-LED and sum power constraints with the design in [9]. In the case of the per-LED power constraint, we assume that P_i for every LED is the same, i.e., $P_i = P_{total}/N$. It is observed that the proposed design outperforms the design in [9]. Moreover, the performance of the design under the sum power constraint has a better performance than the design under the per-LED power constraint, as the per-LED power budget is optimized via the iterative process. The simulation results show that Algorithm 1 is effective to improve the system performance.

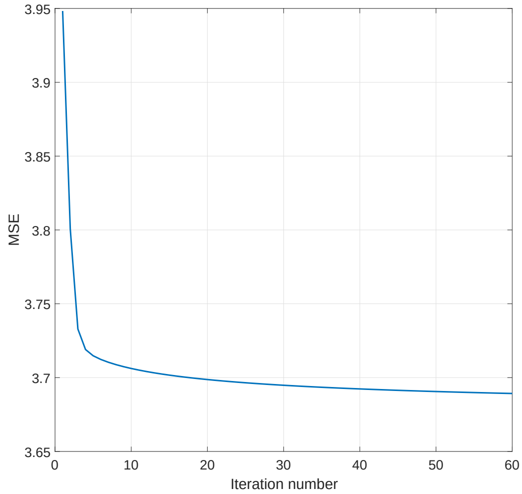

Figure 2: The iterative process of Algorithm 1.

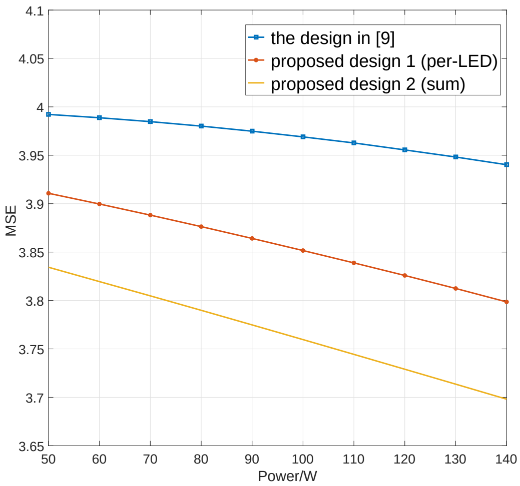

Figure 3: The comparison of the MSE of different precoder and DC bias designs.

V. Conclusion

In this paper, we have investigated the joint precoder and DC bias design problem for a point-to-point MIMO VLC system, which aimed to minimize the MSE between the transmitted and received signals. We have considered the non-negative and two different power constraints, i.e., the per-LED and sum power constraints. We first proposed an efficient method via convex optimization to solve the problem under the per-LED power constraint. Then, we proposed a novel algorithm to address the design problem under the sum power constraint. The performance of the proposed designs was evaluated by the simulation results.

VI. Acknowledgment

This work was supported in part by the 973 Program of China under Grant 2013CB329204, the National Natural Science Foundation of China under Grants 61571107 and 61521061, the Natural Science Foundation of Jiangsu Province under Grant BK20160069, and the Alexander von Humboldt Foundation.

References

[1] S. Rajagopal, R. D. Roberts, and S.-K. Lim, “IEEE 802.15.7 visible light communication: Modulation schemes and dimming support,” *IEEE Commun. Mag.*, vol. 50, no. 3, 2012.

[2] T. Komine and M. Nakagawa, “Fundamental analysis for visible-light communication system using led lights,” *IEEE Trans. Consum. Electron.*, vol. 50, no. 1, pp. 100–107, Feb. 2004.

[3] D. Karunatilaka, F. Zafar, V. Kalavally, and R. Parthiban, “LED based indoor visible light communications: State of the art,” *IEEE Commun. Surveys Tutorials*, vol. 17, no. 3, pp. 1649–1678, thirdquarter 2015.

[4] M. S. A. Mossaad, S. Hranilovic, and L. Lampe, “Visible light communications using OFDM and multiple LEDs,” *IEEE Trans. Commun.*, vol. 63, no. 11, pp. 4304–4313, Nov. 2015.

[5] L. Zeng, D. C. O’Brien, H. L. Minh, G. E. Faulkner, K. Lee, D. Jung, Y. Oh, and E. T. Won, “High data rate multiple input multiple output (MIMO) optical wireless communications using white LED lighting,” *IEEE J. Sel. Areas Commun.*, vol. 27, no. 9, pp. 1654–1662, Dec. 2009.

[6] L. Chen, J. Wang, J. Zhou, D. W. K. Ng, R. Schober, and C. Zhao, “Distributed user-centric scheduling for visible light communication networks,” *Opt. Express*, vol. 24, no. 14, pp. 15 570–15 589, Jul. 2016.

[7] R. Zhang, J. Wang, Z. Wang, Z. Xu, C. Zhao, and L. Hanzo, “Visible light communications in heterogeneous networks: Paving the way for user-centric design,” *IEEE Wireless Commun.*, vol. 22, no. 2, pp. 8–16, Apr. 2015.

[8] K. H. Park, Y. C. Ko, and M. S. Alouini, “On the power and offset allocation for rate adaptation of spatial multiplexing in optical wireless MIMO channels,” *IEEE Trans. Commun.*, vol. 61, no. 4, pp. 1535–1543, Apr. 2013.

[9] Q. Gao, R. Wang, Z. Xu, and Y. Hua, “Joint beamformer and offset design for multi-color visible light communications,” in *2014 Sixth Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2014, pp. 1–6.

[10] B. Li, J. Wang, R. Zhang, H. Shen, C. Zhao, and L. Hanzo, “Multiuser MISO transceiver design for indoor downlink visible light communication under per-LED optical power constraints,” *IEEE Photonics J.*, vol. 7, no. 4, pp. 1–15, Aug. 2015.

[11] H. Ma, L. Lampe, and S. Hranilovic, “Robust MMSE linear precoding for visible light communication broadcasting systems,” in *2013 IEEE Globecom Workshops (GC WKSHPS)*, Dec. 2013, pp. 1081–1086.

[12] J. M. Kahn and J. R. Barry, “Wireless infrared communications,” *Proc. IEEE*, vol. 85, no. 2, pp. 265–298, Feb. 1997.

[13] B. Li, X. Lai, J. Wang, X. Liang, and C. Zhao, “Performance analysis of the imaging receivers using a hemispherical lens for visible light communications,” in *2013 Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2013, pp. 1–5.

[14] H. Burchardt, N. Serafimovski, D. Tsonev, S. Videv, and H. Haas, “VLC: Beyond point-to-point communication,” *IEEE Commun. Mag.*, vol. 52, no. 7, pp. 98–105, Jul. 2014.

[15] J. Wang, Y. Xu, X. Ling, R. Zhang, Z. Ding, and C. Zhao, “PAPR analysis for OFDM visible light communication,” *Opt. Express*, vol. 24, no. 24, pp. 27 457–27 474, Nov. 2016.

[16] X. Ling, J. Wang, X. Liang, Z. Ding, and C. Zhao, “Offset and power optimization for DCO-OFDM in visible light communication systems,” *IEEE Trans. Signal Process.*, vol. 64, no. 2, pp. 349–363, Jan. 2016.

[17] R. A. Horn and C. R. Johnson, *Matrix analysis*. Cambridge university press, 2012.

[18] M. Grant and S. Boyd, “CVX: Matlab software for disciplined convex programming, version 1.21,” *Global Optimization*, pp. 155–210, 2008.

[19] J. F. Sturm, “Using SeDuMi 1.02, a MATLAB toolbox for optimization over symmetric cones,” *Optimization methods and software*, vol. 11, no. 1-4, pp. 625–653, 1999.

[20] J. Wang, D. Zhu, H. Zhang, C. Zhao, J. C. F. Li, and M. Lei, “Resource optimization for cellular network assisted multichannel D2D communication,” *Signal Process.*, vol. 100, pp. 23–31, Jul. 2014.

[21] C. D. Meyer, *Matrix analysis and applied linear algebra*. Society for Industrial and Applied Mathematics, 2000.

[22] A. Bagirov, N. Karmitsa, and M. M. Makela, *Subgradient Methods*. Springer International Publishing, 2014.