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Rate Maximization for Downlink Multiuser Visible Light Communications

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ABSTRACT We are interested in optimizing transmit beamforming for a visible light communication multiuser system such that the achievable sum rate is maximized. We first derive a closed-form sum rate expression via information-theoretic tools. Then, by further including light-emitting diode optical power constraints, we formulate the rate maximization problem in a mathematical optimization form. To address this difficult non-convex problem, we establish an iterative algorithm that exploits sequential parametric convex approximation. Compared with the existing zero-forcing beamforming strategies, the proposed approach does not restrict the co-channel interference to be zero, and thus achieves a higher sum rate, as is validated by simulations.

INDEX TERMS Visible light communication (VLC), transmit beamforming, achievable rate maximization.

I. INTRODUCTION

With rapid development of visible light communication (VLC) [1]–[3], how to boost its spectral efficiency to accommodate the growing demand in high data rate, has become a crucial and challenging topic. Towards this end, a number of recent efforts have been invested in extending advanced radio frequency (RF) techniques such as multiple-input multiple-output (MIMO) [4]–[10] to VLC scenarios.

Concerning the single user system, the authors of [11]–[14] investigated MIMO spatial multiplexing in VLC systems which allows transmitting multiple data streams simultaneously and thus provides a high data rate. The generalization to the multiuser case was studied in [15]–[20]. More specifically, the transmit beamforming optimization under a max-min fairness criterion was discussed in [15] and [16]. In particular, [16] also included an alternative sum-rate maximization design criterion, where the rate objective was derived using the approximated bit error rate (BER) expression for pulse amplitude modulated (PAM) modulation. Different from [16], a recent work [17] considered an information theory based sum rate which is a more fundamental metric for characterizing transmission efficiency. Note that, both [16] and [17] employed a suboptimal zero-forcing (ZF) beamforming scheme which can simplify the derivation but at the cost of performance degradation due to the loss in the desired signal's power. In fact, so far as we know, it remains unknown how to optimize general transmit beamforming for VLC multiuser downlinks such that the information-theoretic rate is maximized.

The goal of this study is to determine the optimal transmit beamforming that maximizes the achievable sum rate of VLC downlink multiuser systems subject to light-emitting diode (LED) optical power constraints. We first derive the sum rate in an explicit form based on the specific feature of VLC channels and information theory. Then, regarding the non-convex beamforming design problem, we are able to find its locally optimal solution via an iterative method which solves one convex problem in each iteration. It is necessary to stress that, compared to the prior work [17] that concerns a similar topic, we maximize the system sum rate directly without adopting the suboptimal zero-forcing strategy. Moreover, the concave-convex procedure used in [17] cannot be applied to solve the rate maximization problem here with a different form. We also note that, the design objective in this paper differs from those in [18] and [19] where performance metrics such as sum mean-squared error (MSE) and BER were adopted.

The remainder of this work is organized as follows. Section II describes the VLC system model we adopt. In Section III, we present the specific problem formulation.

Section IV elaborates on the proposed iterative algorithm. Simulation results are shown in Section V and our conclusions are finally drawn in Section VI.

TABLE 1. Notations.

$\lvert a \rvert$	absolute value of a
$\lVert \mathbf{a} \rVert_F$	Frobenius norm of $\mathbf{a}$
$\mathbf{a}^T$	transpose of $\mathbf{a}$
$\mathbf{e}_l$	unit vector whose lth entry is 1
$\min\{a, b\}$	minimum of a and b
$\mathbb{R}^{m\times n}$	ensemble of $m \times n$ real matrices
$h(A)$	differential entropy of A
$I(A, B)$	mutual information between A and B

Notations: Throughout the paper, we represent vectors and scalars by bold and plain letters, respectively. For clarity, all the notations are listed in Table 1.

II. VLC DOWNLINK MULTIUSER SYSTEM DESCRIPTION

In this paper, we focus on a typical VLC scenario where K user terminals communicate with L LED transmitters simultaneously. The L transmitters fully cooperate with each other and hence the considered system can be viewed as a virtual MIMO system. The transmitter, the channel and the receiver models of the VLC system under concern are respectively elaborated in the sequel.

A. VLC TRANSMITTER MODEL

Since multiple users occupy the same time and frequency resources, there will be inevitable inter-user interference (IUI) that deteriorates the transmission performance. To alleviate the degradation caused by IUI, we leverage linear beamforming at the transmitter which can be interpreted as a linear transformation on the user data [8]–[10]. Denote the transmit beamforming vector of user k by $\mathbf{w}_k \in \mathbb{R}^{L\times 1}$. Then, the beamformed vector takes the form

$$\mathbf{z} = \sum_{k=1}^{K} \mathbf{w}_k s_k \tag{1}$$

where $s_k \in \mathbb{R}$ represents the data symbol of user k with zero mean. Before performing electrical-to-optical conversion via LEDs, we need to add a direct current (DC) offset $\mathbf{p} \in \mathbb{R}^{L\times 1}$ to $\mathbf{z}$ so as to satisfy the specific requirements of the LED input signal, i.e., non-negativity and limited amplitude.

B. VLC CHANNEL MODEL

The classical line-of-sight (LOS) model [11], [14]–[20] will be employed to characterize the optical channel. Specifically, the channel between the lth LED transmitter and the kth user terminal is modeled by

$$g_{k,l} = \begin{cases} \dfrac{(m+1)\rho_k A_k}{2\pi d_{k,l}^2} \cos^m(\phi_{k,l})\cos(\psi_{k,l}) & 0 \le \psi_{k,l} \le \psi_{c,k} \\ 0 & \psi_{k,l} > \psi_{c,k} \end{cases} \tag{2}$$

where m denotes the Lambertian emission order, ρ_k represents the photodiode (PD) responsivity of the kth receiver, A_k stands for the receiver collection area of user k, $d_{k,l}$ denotes the distance between the kth user and the lth LED, $\phi_{k,l}$ is the irradiance angle, $\psi_{k,l}$ is the incidence angle, and $\psi_{c,k}$ is the receiver field of view (FOV). A_k is obtained by

$$A_k = \frac{\alpha_k^2}{\sin^2(\psi_{c,k})} A_{PD,k} \tag{3}$$

where α_k and $A_{PD,k}$ represent the optical concentrator refractive index and the PD area, respectively.

C. VLC RECEIVER MODEL

The received signal after direct detection and DC removal at the kth receiver is given by

$$y_k = \mathbf{g}_k^T \mathbf{w}_k s_k + \mathbf{g}_k^T \sum_{j=1, j\neq k}^{K} \mathbf{w}_j s_j + n_k \tag{4}$$

where $\mathbf{g}_k^T$ denotes the channel between the kth user and the L LEDs, and n_k stands for the zero-mean additive white Gaussian noise that consists of both shot and thermal noises. The variance of n_k takes the form [11], [16]–[18], [20]

$$\sigma_{n_k}^2 = 2e_{ch}(P_{r,k} + 2\pi\rho_k \chi_{amb} A_k(1-\cos(\psi_{c,k})))B + i_{amp}^2 B \tag{5}$$

where e_{ch}, $P_{r,k} = \mathbf{g}_k^T \mathbf{p}$, χ_{amb}, B and i_{amp} represent the electronic charge, the average received optical power, the ambient light photocurrent, the system bandwidth and the pre-amplifier noise current density, respectively.

III. ACHIEVABLE RATE MAXIMIZATION PROBLEM FORMULATION

Based on the VLC multiuser system model presented in Section II, we are now prepared to formulate the corresponding achievable rate maximization problem with respect to the transmit beamforming vector $\mathbf{w}_k$. Firstly, we derive a closed-form expression for the achievable sum rate of the considered system. According to the kth user's received signal model in (4) and information theory [21], the channel capacity for user k is lower bounded by

$$\begin{aligned} C_k &\ge I(X_k; Y_k) \\ &= h(Y_k) - h(Y_k|X_k) \\ &= h(X_k + T_k) - h(T_k) \\ &\overset{(a)}{\ge} \frac{1}{2}\log\left(e^{2h(X_k)} + e^{2h(T_k)}\right) - h(T_k) \\ &= \frac{1}{2}\log\left(1 + \frac{e^{2h(X_k)}}{e^{2h(T_k)}}\right) \end{aligned} \tag{6}$$

where X_k, T_k, and Y_k denote the random variables corresponding to the desired signal $x_k = \mathbf{g}_k^T \mathbf{w}_k s_k$, the sum of interference and noise $t_k = \mathbf{g}_k^T \sum_{j=1,j\neq k}^{K} \mathbf{w}_j s_j + n_k$, and the received signal y_k, respectively. Moreover, inequality (a) is due to the entropy power inequality (EPI) [21, Th. 17.7.3].

Then, following [22] and [23], we assume that the transmit symbol s_k, $k = 1, \cdots, K$ is uniformly distributed over the interval $[-1, 1]$, from which we obtain $h(X_k) = \log(2|\mathbf{g}_k^T \mathbf{w}_k|)$ and thus have

$$C_k \geq \frac{1}{2} \log\left(1 + \frac{4|\mathbf{g}_k^T \mathbf{w}_k|^2}{e^{2h(T_k)}}\right). \tag{7}$$

Notice that, $h(T_k)$ must be upper bounded by the differential entropy of a Gaussian random variable with variance $\sigma_{t_k}^2 = \sum_{j=1,j\neq k}^K \sigma_{s_j}^2 |\mathbf{g}_k^T \mathbf{w}_j|^2 + \sigma_{n_k}^2$, i.e., $h(T_k) \leq \frac{1}{2}\log(2\pi e \sigma_{t_k}^2)$ [21, Th. 17.2.3], where $\sigma_{s_j}^2$ denotes the variance of the transmit symbol s_j and equals $\frac{1}{3}$ due to the uniform distribution obeyed by the transmit symbol. Thereby, we determine an explicit lower bound to C_k by

$$C_k \geq \frac{1}{2} \log\left(1 + \frac{2|\mathbf{g}_k^T \mathbf{w}_k|^2}{\pi e \left(\sum_{j=1,j\neq k}^K \frac{1}{3}|\mathbf{g}_k^T \mathbf{w}_j|^2 + \sigma_{n_k}^2\right)}\right) \triangleq R_k \tag{8}$$

which is an achievable rate for user k. Accordingly, the sum rate of all K users takes the form

$$R = \sum_{k=1}^K R_k = \sum_{k=1}^K \frac{1}{2}\log\left(1 + \frac{2|\mathbf{g}_k^T \mathbf{w}_k|^2}{\pi e \left(\frac{1}{3}\sum_{j\neq k} |\mathbf{g}_k^T \mathbf{w}_j|^2 + \sigma_{n_k}^2\right)}\right). \tag{9}$$

Now let us investigate the constraint imposed on the transmit beamformer $\mathbf{w}_k$ by exploiting the fact that the LED input signal is non-negative and its amplitude is bounded. From Section II-A, we know that the LED input is $\mathbf{q} = \mathbf{z} + \mathbf{p} = \sum_{k=1}^K \mathbf{w}_k s_k + \mathbf{p}$, whose entries lie in the interval $[0, P_m]$, where P_m is the maximum allowed signal amplitude. Consequently, it can be deduced that $\mathbf{w}_k$ satisfies

$$\sum_{k=1}^K |\mathbf{e}_l^T \mathbf{w}_k| \leq \min\{p_l, P_m - p_l\} \triangleq p_l', \quad l = 1, \cdots, L \tag{10}$$

where p_l is the lth entry of $\mathbf{p}$. At this step, we are ready to formulate the achievable rate maximization problem for VLC multiuser downlinks, which is expressed by

$$\begin{aligned} \underset{\mathbf{w}_k}{\text{maximize}} \quad & \sum_{k=1}^K \frac{1}{2}\log\left(1 + \frac{2|\mathbf{g}_k^T \mathbf{w}_k|^2}{\pi e \left(\frac{1}{3}\sum_{j\neq k} |\mathbf{g}_k^T \mathbf{w}_j|^2 + \sigma_{n_k}^2\right)}\right) \\ \text{subject to} \quad & \sum_{k=1}^K |\mathbf{e}_l^T \mathbf{w}_k| \leq p_l', \quad l = 1, \cdots, L. \end{aligned} \tag{11}$$

Due to the complicated non-concave objective function, this is clearly a non-convex problem and cannot be readily addressed. Nonetheless, in the subsequent section, we will develop an efficient iterative algorithm that involves solving a sequence of convex problems and returns a locally optimal solution to the rate maximization problem in (11).

IV. RATE MAXIMIZED BEAMFORMING FOR VLC MULTIUSER DOWNLINKS

Regarding the non-convex rate maximization problem shown in (11), we aim to seek for its locally optimal solution in this section. To begin with, we introduce auxiliary variables u_k, $k = 1, \cdots, K$ and obtain a reformulation of problem (11) given by

$$\begin{aligned} \underset{\mathbf{w}_k, u_k}{\text{maximize}} \quad & \sum_{k=1}^K \frac{1}{2}\log\left(1 + \frac{2u_k}{\pi e}\right) \\ \text{subject to} \quad & \frac{|\mathbf{g}_k^T \mathbf{w}_k|^2}{\frac{1}{3}\sum_{j\neq k} |\mathbf{g}_k^T \mathbf{w}_j|^2 + \sigma_{n_k}^2} \geq u_k, \quad k = 1, \cdots, K \\ & \sum_{k=1}^K |\mathbf{e}_l^T \mathbf{w}_k| \leq p_l', \quad l = 1, \cdots, L. \end{aligned} \tag{12}$$

Due to the first K non-convex constraints, it is still hard to solve the above problem in a convenient way. To proceed, we rewrite this problem by

$$\begin{aligned} \underset{\mathbf{w}_k, u_k, v_k}{\text{maximize}} \quad & \sum_{k=1}^K \frac{1}{2}\log\left(1 + \frac{2u_k}{\pi e}\right) \\ \text{subject to} \quad & |\mathbf{g}_k^T \mathbf{w}_k|^2 \geq u_k v_k^2, \quad k = 1, \cdots, K \\ & \frac{1}{3}\sum_{j\neq k} |\mathbf{g}_k^T \mathbf{w}_j|^2 + \sigma_{n_k}^2 \leq v_k^2, \quad k = 1, \cdots, K \\ & \sum_{k=1}^K |\mathbf{e}_l^T \mathbf{w}_k| \leq p_l', \quad l = 1, \cdots, L \end{aligned} \tag{13}$$

where v_k's are auxiliary variables. We can readily prove by contradiction[1] that $\mathbf{g}_k^T \mathbf{w}_k$ can be non-negative at the optimal point. Accordingly, it does not lose optimality to express the constraint $|\mathbf{g}_k^T \mathbf{w}_k|^2 \geq u_k v_k^2$ by

$$\mathbf{g}_k^T \mathbf{w}_k \geq \sqrt{u_k} v_k. \tag{14}$$

Moreover, it is evident to see that the constraint $\frac{1}{3}\sum_{j\neq k} |\mathbf{g}_k^T \mathbf{w}_j|^2 + \sigma_{n_k}^2 \leq v_k^2$ is tantamount to the following convex form:

$$\left\| \left[\frac{\mathbf{g}_k^T \mathbf{w}_1}{\sqrt{3}}, \ldots, \frac{\mathbf{g}_k^T \mathbf{w}_{k-1}}{\sqrt{3}}, \frac{\mathbf{g}_k^T \mathbf{w}_{k+1}}{\sqrt{3}}, \ldots, \frac{\mathbf{g}_k^T \mathbf{w}_K}{\sqrt{3}}, \sigma_{n_k} \right] \right\|_F \leq v_k. \tag{15}$$

Therefore, based on (14) and (15), we are able to transform problem (13) into a more tractable form as

$$\begin{aligned} \underset{\mathbf{w}_k, u_k, v_k}{\text{maximize}} \quad & \sum_{k=1}^K \frac{1}{2}\log\left(1 + \frac{2u_k}{\pi e}\right) \\ \text{subject to} \quad & \mathbf{g}_k^T \mathbf{w}_k \geq \sqrt{u_k} v_k, \quad k = 1, \cdots, K \\ & \left\| \left[\frac{\mathbf{g}_k^T \mathbf{w}_1}{\sqrt{3}}, \ldots, \frac{\mathbf{g}_k^T \mathbf{w}_{k-1}}{\sqrt{3}}, \frac{\mathbf{g}_k^T \mathbf{w}_{k+1}}{\sqrt{3}}, \ldots, \frac{\mathbf{g}_k^T \mathbf{w}_K}{\sqrt{3}}, \sigma_{n_k} \right] \right\|_F \leq v_k, \quad k = 1, \cdots, K \\ & \sum_{k=1}^K |\mathbf{e}_l^T \mathbf{w}_k| \leq p_l', \quad l = 1, \cdots, L. \end{aligned} \tag{16}$$

[1]For any optimal $\mathbf{w}_k^*$, it is always possible to construct another feasible solution $\tilde{\mathbf{w}}_k^* = \text{sgn}(\mathbf{g}_k^T \mathbf{w}_k^*)\mathbf{w}_k^*$ which satisfies $\mathbf{g}_k^T \tilde{\mathbf{w}}_k^* \geq 0$ and attains the identical optimal value as $\mathbf{w}_k^*$.

Algorithm 1 An SPCA Based Algorithm for Solving Problem (11)

Initialization: set initial $\theta_k^{(0)}$, iteration index $j = 0$, and convergence accuracy ϵ.
repeat
  Solve the convex problem in (17).
  Set $\theta_k^{(j+1)} = \frac{\sqrt{u_k^{(j)}}}{v_k^{(j)}}$.
  $j = j + 1$.
until convergence.

Then, we adopt the sequential parametric convex approximation (SPCA) method in [24] to handle the non-convex constraint in (14).[2] The key idea of SPCA is to replace the non-convex term $\sqrt{u_k}v_k$ in (14) by its convex lower bound $\frac{u_k}{2\theta_k} + \frac{v_k^2\theta_k}{2}$ with a given θ_k, which can be achieved when $\theta_k = \frac{\sqrt{u_k}}{v_k}$. Clearly, after the replacement, (14) becomes a convex constraint $\mathbf{g}_k^T\mathbf{w}_k \geq \frac{u_k}{2\theta_k} + \frac{v_k^2\theta_k}{2}$. The values of $\mathbf{w}_k, u_k, v_k$ and θ_k are updated iteratively in SPCA. To be more specific, during the jth iteration of the SPCA method, we need to solve the convex problem below

$$\begin{aligned} &\underset{\mathbf{w}_k, u_k, v_k}{\text{maximize}} \sum_{k=1}^{K} \frac{1}{2}\log\left(1 + \frac{2u_k}{\pi e}\right) \\ &\text{subject to } \mathbf{g}_k^T\mathbf{w}_k \geq \frac{u_k}{2\theta_k^{(j)}} + \frac{v_k^2\theta_k^{(j)}}{2}, \quad k = 1, \cdots, K \\ &\qquad \left\| \left[\frac{\mathbf{g}_k^T\mathbf{w}_1}{\sqrt{3}}, \ldots, \frac{\mathbf{g}_k^T\mathbf{w}_{k-1}}{\sqrt{3}}, \frac{\mathbf{g}_k^T\mathbf{w}_{k+1}}{\sqrt{3}}, \ldots, \frac{\mathbf{g}_k^T\mathbf{w}_K}{\sqrt{3}}, \right.\right. \\ &\qquad\qquad \left.\left. \sigma_{n_k} \right] \right\|_F \leq v_k, \quad k = 1, \cdots, K \\ &\qquad \sum_{k=1}^{K} |\mathbf{e}_l^T\mathbf{w}_k| \leq p_l^{'}, \quad l = 1, \cdots, L \end{aligned} \tag{17}$$

where $\theta_k^{(j)} = \frac{\sqrt{u_k^{(j-1)}}}{v_k^{(j-1)}}$ with $u_k^{(j-1)}$ and $v_k^{(j-1)}$ denoting the optimal solutions to u_k and v_k in the $(j-1)$th iteration. Due to the convexity of problem (17), we can find its optimal solution via interior-point algorithms in polynomial time, which in general apply Newton's method to a sequence of equality constrained problems [26, Ch. 11]. In the sequel, we summarize the procedure of solving problem (11) in Algorithm 1.

Remark 1: Following the analogous reasoning in [24] and [25], we can prove that Algorithm 1 converges to a Karush-Kuhn-Tucker (KKT) point of problem (11). Moreover, we find via simulations that it is desirable to choose the suboptimal ZF beamforming in [17, Sec. 3.2] as the initial point, under which the proposed algorithm can converge in a few iterations. Finally, Algorithm 1 has a polynomial complexity since it involves solving one convex problem in each iteration.

[2]SPCA has also been utilized in some recent works on rate optimization for RF communication systems, e.g., [25].

TABLE 2. System parameter configuration.

Parameters	Values
Room size	5 m×5 m×3 m
Number of LED arrays L	9
Number of LEDs per array	3600 (60×60)
LED pitch	1 cm
LED Lambertian emission order m	1
Number of users K	3
Optical concentrator refractive index α_k	1.5
PD area $A_{PD,k}$	1 cm^2
PD responsivity ρ_k	0.4 A/W
Receiver FOV $\psi_{c,k}$	62°
Pre-amplifier noise current density i_{amp}	5 pA/Hz$^{-1/2}$
Ambient light photocurrent χ_{amb}	10.93 A/m^2/Sr
System bandwidth B	30 MHz

TABLE 3. The coordinates of 9 LED arrays.

LED array coordinates I	LED array coordinates II
(1.25 m, 1.25 m, 3 m)	(1.85 m, 1.85 m, 3 m)
(2.5 m, 1.25 m, 3 m)	(2.5 m, 1.85 m, 3 m)
(3.75 m, 1.25 m, 3 m)	(3.15 m, 1.85 m, 3 m)
(1,25 m, 2.5 m, 3 m)	(1.85 m, 2.5 m, 3 m)
(2.5 m, 2.5 m, 3 m)	(2.5 m, 2.5 m, 3 m)
(3.75 m, 2.5 m, 3 m)	(3.15 m, 2.5 m, 3 m)
(1.25 m, 3.75 m, 3 m)	(1.85 m, 3.15 m, 3 m)
(2.5 m, 3.75 m, 3 m)	(2.5 m, 3.15 m, 3 m)
(3.75 m, 3.75 m, 3 m)	(3.15 m, 3.15 m, 3 m)

TABLE 4. The coordinates of 3 users.

User coordinates I	User coordinates II
(2 m, 2.25 m, 0.85 m)	(2.05 m, 2.25 m, 0.85 m)
(1 m, 3.5 m, 0.85 m)	(1.8 m, 1.85 m, 0.85 m)
(2 m, 3 m, 0.85 m)	(2 m, 2 m, 0.85 m)

V. SIMULATION RESULTS

We now conduct simulations to test the performance of the proposed rate maximization algorithm. For the sake of comparison, we also simulate both the optimal ZF beamforming design ("ZF Opt") and the suboptimal one ("ZF Subopt") developed in [17, Sec. 3.1] and [17, Sec. 3.2], respectively, which are two existing beamforming methods that aim to maximize the information-theoretic rate of VLC multiuser downlinks, however, under a ZF constraint. We list the system parameters used for simulations in Table 2. The coordinates of the LED arrays and the users are shown in Tables 3 and 4,

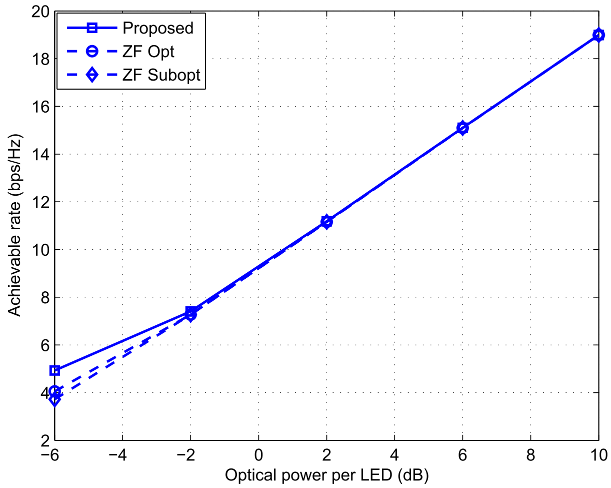


FIGURE 1. Achievable rate performance comparison of different beamforming methods (Case I).

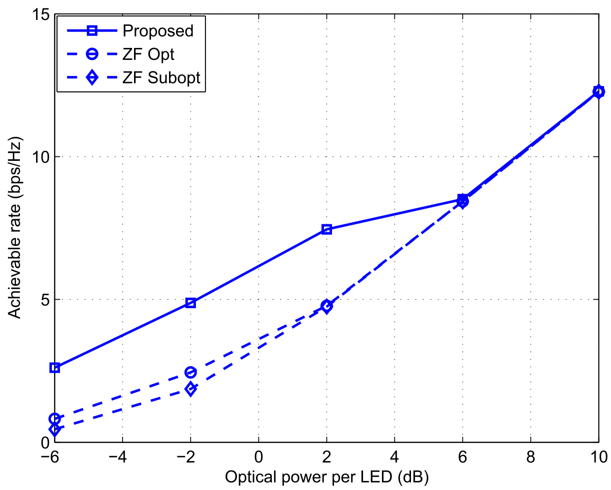


FIGURE 2. Achievable rate performance comparison of different beamforming methods (Case II).

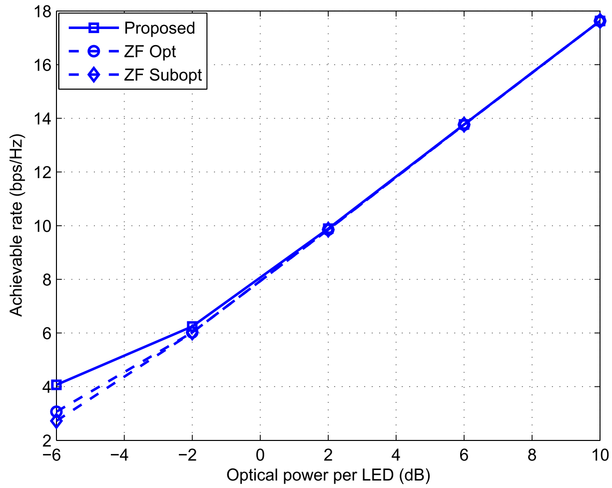


FIGURE 3. Achievable rate performance comparison of different beamforming methods (Case III).

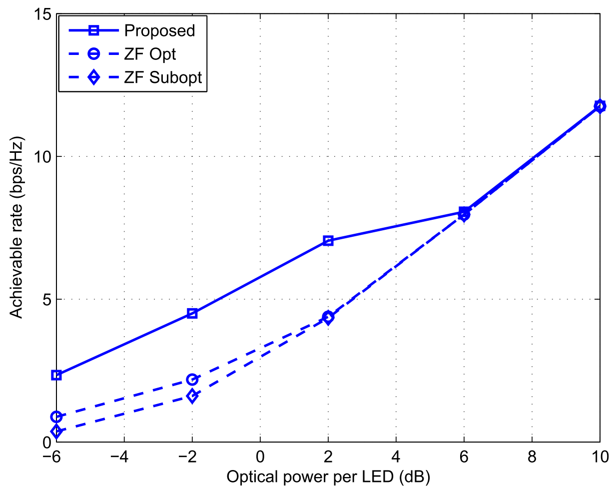


FIGURE 4. Achievable rate performance comparison of different beamforming methods (Case IV).

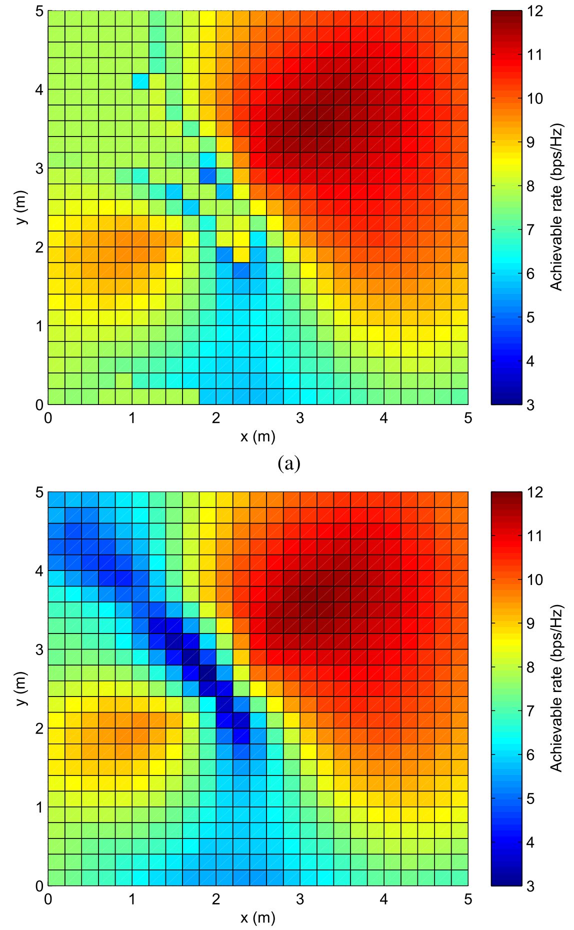
respectively. All the four combinations of LED and user locations will be considered, which are

- Case I: LED coordinate I + user coordinate I
- Case II: LED coordinate I + user coordinate II
- Case III: LED coordinate II + user coordinate I
- Case IV: LED coordinate II + user coordinate II.

In general, when the distance between the LED arrays or the users gets shorter, the corresponding channel correlation will be higher. For instance, the channel correlations under Case II and Case III are both higher than that under Case I.

The achievable rate performance comparisons under the above four cases are demonstrated in Figs. 1–4. From these figures, we find that the proposed optimal beamforming method always achieves a higher rate than the ZF based strategies, particularly when the LED optical power is low or the channel correlation is high. The underlying reason for such phenomenon is that the proposed design maximizes the system sum rate directly without imposing a ZF constraint which can reduce the desired signal's power and accordingly lead to a performance loss. It can also be observed from the simulation results that the achievable rates of different schemes all decrease when the LED arrays or the users get closer. This is due to the fact that the performance of spatial division based downlink multiuser transmissions degrades if the channel correlation is high.

In Fig. 5, we show the achievable rate distributions of the proposed optimal beamforming and optimal ZF beamforming. To obtain this figure, we fix the coordinates of 2 users with [2, 2.25, 0.85] and [1, 3.5, 0.85], and calculate the achievable sum rate as a function of the third user's coordinate. Moreover, the optical power per LED is set to 0 db. It can be seen from Fig. 5 that both methods achieve a high sum rate when the third user is far from the other two users due to the low channel correlation. Furthermore, the proposed scheme outperforms the ZF based strategy by an evident gain, especially when the third user approaches the



(a)

(b)

FIGURE 5. Achievable rate distribution comparison between two beamforming schemes. (a) Proposed optimal beamforming. (b) Optimal ZF beamforming.

other two. For instance, when the coordinate of the third user is [2, 2.4, 0.85], the achievable rates of the proposed method and ZF beamforming are 7.8641 bps/Hz and 3.8757 bps/Hz, respectively.

VI. CONCLUSIONS

We optimized transmit beamforming for a VLC downlink multiuser system with the goal of maximizing its achievable sum rate. A closed-form expression for the rate objective was first derived, based upon which we formulated the design problem mathematically, and furthermore developed an iterative algorithm that converges to a locally optimal solution. Simulations indicate that the proposed optimal beamforming outperforms conventional ZF based schemes by noticeable gains, especially for low transmit optical powers or high channel correlations.

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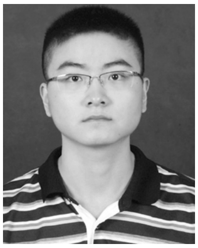

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