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A power-efficient ZF precoding scheme for multi-user indoor visible light communication systems

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ABSTRACT

In this study, we propose a power-efficient ZF precoding scheme for visible light communication (VLC) downlink multi-user multiple-input-single-output (MU-MISO) systems, which incorporates the zero-forcing (ZF) and the characteristics of VLC systems. The main idea of this scheme is that the channel matrix used to perform pseudoinverse comes from the set of optical Access Points (APs) shared by more than one user, instead of the set of all involved serving APs as the existing ZF precoding schemes often used. By doing this, the waste of power, which is caused by the transmission of one user's data in the un-serving APs, can be avoided. In addition, the size of the channel matrix needs to perform pseudoinverse becomes smaller, which helps to reduce the computation complexity. Simulation results in two scenarios show that the proposed ZF precoding scheme has higher power efficiency, better bit error rate (BER) performance and lower computation complexity compared with traditional ZF precoding schemes.

1. Introduction

The conflict between the increasing demand for wireless data services and the growing scarcity of frequency spectrum prompts people to seek new solutions for future wireless communication systems [1]. Because of license-free light spectrum, low-cost devices and immunity to radio frequency (RF) interference, visible light communication (VLC) based on light emitting diode (LED) has become a promising candidate to address the current challenges in wireless communications [2,3]. In a VLC system, data are modulated onto the intensity (power) of the optical signals at the transmitter. At the receiver, a photo detector (PD) is employed to convert the optical power signals into electrical signals. Usually light installations are equipped with multiple LEDs to meet the requirement of luminous intensity, which leads to the overlaps among the emissions of different luminaries [4]. When multiple users in the overlapping areas are scheduled, interference is unavoidable [5]. As one of the effective measures for interference elimination, precoding techniques have been extensively researched in RF wireless communication systems [6,7]. Unlike RF systems, the transmitted signals in VLC systems are real and non-negative because of intensity modulation and direct detection (IM/DD). The elements of the VLC channel matrix are also real and non-negative because of the propagation characteristics of optical channels [8]. To summarize, conventional RF precoding techniques cannot be applied to VLC systems directly.

Recently, many studies have focused on precoding techniques in VLC systems [9–13]. In [9], a block diagonalization (BD) based on precoding schemes was applied to multi-user VLC systems. A locally optimal linear precoding method was proposed in [10] for VLC MU-MISO relying on the objective function of minimizing the total mean-squared error between the received and legitimate transmitted signals of the user. In [11], a pseudoinverse based zero-forcing (ZF) strategy conceived for MU-MISO brocading systems was considered. The author in [12] maximized the achievable rate for VLC MU-MISO downlink systems deployed with a ZF precoding scheme. The bit error rate (BER) performance evaluations of three precoding schemes under different values of channel estimation error were presented in [13]. All these works on precoding techniques in VLC systems can eliminate or reduce the multi-user interference (MUI).

Since each user has a limited receiver field of view (FOV), they can only receive signals from the APs residing within their FOV. When a user can receive data from an AP, we name this AP as a serving AP for this user. When two users can receive data from an AP, we name this AP as a shared AP for these two users. the MUI between two users can only exist when they have shared AP. In the existing ZF (or others) precoding schemes, the channel matrix used to perform pseudoinverse is derived from the collection of all serving APs to scheduled users. None of the elements in the precoding matrix based on pseudoinverse is zero. The application of this precoding matrix to the VLC systems means that each user's data would be transmitted by all the serving APs, regardless of whether a user can receive its data or not. This procedure would result in the waste of transmitting power and much

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computing burden when the set of the shared APs is the proper subset of the collection of all active users' serving APs.

Against the above-mentioned problem, we propose a power-efficient precoding scheme in this paper. Firstly, we divide all serving APs into two parts. The first part is the collection of the shared APs, each of which serves at least two active users. The second part is the combination of the rest APs, each of which serves only one active user. Then, we take two different handing mechanisms to get the precoding matrices corresponding to these two parts. Finally, we combine these two results and get the whole precoding matrix for all active users. The processing procedure will be described in detail in the following sections. In this paper, we assume that the active users group can be selected by scheduling algorithm [14,15], and the detail is not involved here.

The remainder of this paper is organized as follows. The VLC MU-MISO systems model is described in Section 2. Section 3 shows the design details of our proposed precoding scheme. Performance analysis and simulation results are outlined in Section 4, and finally concluding remarks are presented in Section 5.

2. System model

2.1. Transmitter model

Consider an single-cell multi-user indoor VLC system with N APs cooperating to broadcast information to K single-photodiode users. For modulation we consider on-off keying (OOK) as often applied in VLC systems. Without loss of generality, we define $s_k = \{\pm 1\}$ as the data symbol intended for the k-th user, and $\mathbf{s} = [s_1, \ldots, s_K]^T$ is the data vector for all the active users. Note that $\mathbf{s}$ is a zero-mean current signal, it does not affect the illumination level. After precoded by matrix $\mathbf{W} = [\mathbf{w}_1, \ldots, \mathbf{w}_K] \in \mathbf{R}^{N*K}$, the signal vector is given by

$$\mathbf{f} = [f_1, \ldots, f_N]^T = \mathbf{W}\mathbf{s} = \sum_{k=1}^{K} \mathbf{w}_k s_k \tag{1}$$

where f_n denotes the data allocated to the n-th AP, and $\mathbf{w}_k \in R^{N*1}$ is the precoding vector of the k-th user. Also note that the ZF precoding ensures that the interference at the receiver is suppressed to zero, it does not affect the illumination level. In order to set the average radiated optical power and, consequently, adjust the illumination level, the direct current (DC) bias needs to be added to the transmitted signals. Here it is assumed that all LEDs have the same DC bias currant I_{DC}. Then, the signal $\mathbf{x} = [x_1, \ldots, x_N]^T$ transmitted by the APs can be expressed as

$$\mathbf{x} = \mathbf{f} + \mathbf{d} \tag{2}$$

where $\mathbf{d} = [I_{DC}, \ldots, I_{DC}]^T$. Similar to the nonlinearity of the RF transmitters, VLC systems also have a limited linear region [16]. In order to maintain linear current-light conversion and avoid clipping, the total input current must be constrained with some range, which we set as $I_{DC} + \alpha I_{DC}$. Where $0 \le \alpha \le 1$ is termed as the modulation index. Thus, the input data must satisfy the amplitude constraint

$$|f_n| = |\sum_{k=1}^{K} w_{kn} s_k| \le \alpha I_{DC}, \quad n = 1, \ldots, N \tag{3}$$

Since $s_k = \{\pm 1\}$, the optical power constraint of per-AP becomes

$$\sum_{k=1}^{K} |w_{kn}| \le \alpha I_{DC}, \quad n = 1, \ldots, N \tag{4}$$

where w_{kn} is the element of $\mathbf{W}$ in the n-th row and k-th column.

After the procedure of the electro-optical conversion, the transmitted optical signal is given by

$$\mathbf{t} = \gamma \mathbf{x} \tag{5}$$

where γ is the current-to-light conversion efficiency of the LED.

2.2. Receiver model

According to [16], the channel gain between the k-th receiver and the n-th AP can be represented by

$$h_{kn} = \begin{cases} \dfrac{(m+1)A\cos^m(\phi_{kn})}{2\pi D_{kn}^2} T_S(\psi_{kn}) g(\psi_{kn}) \cos(\psi_{kn}) & 0 \le \psi_{kn} \le \psi_c \\ 0 & \psi_{kn} > \psi_c \end{cases} \tag{6}$$

where A is the physical area of the detector in a PD, D is the distance between a transmitter and a receiver, ψ_{kn} is the angle of incidence, ϕ_{kn} is the angle of irradiance, $T_S(\psi_{kn})$ is the gain of an optical filter, and $g(\psi_{kn})$ is the gain of an optical concentrator, ψ_c denotes the width of the field of vision at a receiver.

In the receiver, a PD of responsivity R converts the incident optical power into the proportional current. Suppose that the co-channel interference can be totally eliminated by the ZF precoding. After the DC bias is removed, the received signal at the k-th user terminal can be expressed as

$$r_k = R\gamma \mathbf{h}_k \mathbf{w}_k s_k + n_k \tag{7}$$

where $\mathbf{h}_k = [h_{k1}, \ldots, h_{kN}]$ represents the channel vector of the k-th user, and n_K is the real-valued additive white Gaussian noise (AWGN) constituted by the shot noise plus thermal noise in VLC systems [8], which can be calculated by $\sigma_k^2 = \sigma_{shot}^2 + \sigma_{thermal}^2$. It is known that the shot noise is due to ambient illumination from sunlight and/or other light sources, and the thermal noise which is dominant, is caused by electronic circuits in the receiver.

Consequently, the signal to interference plus noise ratio (SINR) of the output received electrical signal at j-th user is given by

$$\mathrm{SINR}_k = (R\gamma \mathbf{h}_k \mathbf{w}_k s_k)^2/\sigma_k^2 = (R\gamma \mathbf{h}_k \mathbf{w}_k)^2/\sigma_k^2 \tag{8}$$

3. Power-efficient ZF precoding scheme designs for MU-MISO indoor VLC

Suppose that K single-photodiode users are scheduled at the same slot by N corresponding transmitting VLC APs. In order to clearly describe our scheme, we utilize the concept of virtual cell. All the serving APs and the scheduled users form a virtual cell. Let $\nu_U = \{u_k | k = 1, \ldots, K\}$ denotes the collection of active users, and $\nu_A = \{AP_n | n = 1, \ldots, N\}$ represents the set of all serving APs. We use ν_{u_k} to denote the set of the k-th user's serving AP, and $\nu_{u_k} = \{AP_j | \{j\} \in \{1, 2, \ldots, N\}\}$. Then the set of the shared APs for the i-th user and the j-th user can be represented as $\nu_{c_{ij}} = \nu_{u_i} \cap \nu_{u_j}, i, j = 1, \ldots, K, i \ne j$. Consequently, the total set of the shared APs in this virtue cell can be defined as $\nu_C = \nu_{c_{12}} \cup \nu_{c_{13}} \cup \cdots \cup \nu_{c_{1K}} \cup \nu_{c_{23}} \cdots \cup \nu_{c_{(K-1)K}}$. For the requirement of privacy, the distance between two users can not be too close in a room. Moreover, the active user group satisfying the distance requirement can be selected by appropriate scheduling algorithms [17]. So it is reasonable to assume the case that all active users have exactly the same serving APs is less likely to happen. That is to say that the expression $\nu_C \subset \nu_A$ is valid in most realistic scenarios.

From the analysis above, we can see that the size of set ν_C (we set M) is no greater than N. We assume that the channel estimation can be done just as RF systems. The channel state information (CSI) can be provided to the transmitter by another medium such as uplink, which has been thought as a reasonable model [2]. Then we can get the local channel matrix $\widetilde{\mathbf{H}} \in R^{K*M}$, which is composed by the channel vector spanning from the APs in the set ν_C to all the active users. The local precoding matrix $\widetilde{\mathbf{W}}$ based on ZF can be written as

$$\widetilde{\mathbf{W}} = \widetilde{\mathbf{H}}^{\dagger} diag\{[\lambda_1, \ldots \lambda_k]\} \tag{9}$$

The diagonal matrix $diag\{[\lambda_1, \ldots \lambda_k]\}$ is introduced to enforce the per-