Multiuser Multidetector Indoor Visible Light Communication System

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Abstract—We present an optimal fair power allocation and receiver combination scheme for multiuser indoor visible light communication systems using CDMA. MIMO diversity is achieved by using multiple LEDs and photodetectors with different orientations, resulting in a greater than 3 dB power advantage compared with MISO schemes.

I. INTRODUCTION

Visible light communication (VLC) is a new optical wireless communication technique using light emitting diodes (LED) as transmitters. Since VLC generates no electromagnetic interference, is environmentally friendly, can provide large unregulated spectral resources and higher security, it has a wide range of potential applications, such as in airplanes and hospitals where RF is not allowed [1].

In recent years, a strong research emphasis has been multiuser VLC. To provide data transmission for multiple users with low multi-access interference (MAI), a multiple input multiple output (MIMO) technique using a precoding algorithm is proposed in [2]. Another research direction to limit interference is to wisely allocate the transmitted power to different users. In [3], a transmitted power allocation scheme for the subcarriers in orthogonal frequency multiple access (OFMDA) using a single photodetector is described. Recently, in [4] we proposed a power allocation joint optimization algorithm (PAJO) with a single photodetector that has a better BER performance compared with other techniques. Using multiple photodetectors in each receiver is a novel approach proposed recently in [5], [6]. In these models, each photodetector has a different orientation, and since this model has a larger acceptance angle, the signal to interference plus noise ratio (SINR) is improved [6].

In this paper, the multiple detector model proposed in [6] is used to improve the BER performance of the PAJO algorithm. On this basis, we propose a combined optimal power allocation and received signal combination scheme we call M-PAJO (multi-detector power allocation joint optimization). A code division multiplexing access (CDMA) technique is used to support multiple users. We weigh the signals received from the photodetectors differently and then apply a minimum mean square error (MMSE) filter for each user to eliminate the MAI. The transmitter powers and receiver weights are optimized to maximize the minimum SINR among all the users. According to simulation results, the proposed M-PAJO has a power advantage greater than 3 dB compared with the multiple-input single-output (MISO) scheme proposed in [4].

The remainder of the paper is organized as follows. The system model and joint optimization are described in Section II. In Section III, numerical results are discussed. Finally, the paper is concluded in Section IV.

II. SYSTEM DESCRIPTION

A. MIMO Channel Model

In this paper, intensity-modulation and direct-detection (IM/DD) are applied in the indoor environment because of the incoherence of the LED light. We use what we call the 25-LED model described in [4] as a transmitter, where each LED can be controlled separately. The multi-detector model used as a receiver in this paper is shown in Fig. 1, where each photodetector has a different orientation that depends on its inclination angle [6].

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We assume the time differences between the arrival of signal components from different lamps are small enough compared with the symbol period to be ignored. We also assume that the channel gain only contains the line of sight component. Thus, considering the multi-detector model of the receiver, the channel gain between the qth LED and vth detector of the kth user can be written as

$$h_{qkv} = A_r (m + 1) \cos^m (\vec{r}_{qk}, \vec{l}_q) \cos (\vec{r}_{qk}, \vec{z}_{kv})$$

where $A_r$ is the area of each photodetector, $d_{qk}$ is the distance between the LED and the user, $\vec{r}_{qk}$ is the unit vector pointing from the LED towards the user, $\vec{l}_q$ is the vth detector’s of kth user normal unit vector, and $\vec{z}_{kv}$ represents the radiation unit direction vector for the qth LED. In (1), the notation $\langle x, y \rangle$ represents the angle between vectors $x$ and $y$. Fig. 2 illustrates
After the channel, the signal received by the $Q$th LED needs to be applied to the allocated powers. Since the power of $\sum P_k$ is the power limit of $k$, where $m$ is the Lambertian mode of the light source, which is related to the LED’s semiangle $\Phi_{1/2}$ by $m = \frac{\ln 2}{\sin \Phi_{1/2}}$.

We assume that the VLC network has $Q$ LEDs with $K$ users, each user has $V$ detectors with different orientations. Let $s_k(t)$ be the signal that is intended for user $k$ at a given symbol time. The $q$th LED sends a linear combination of the users’ data as

$$x_q(t) = \sum_{k=1}^{K} P_{qk} s_k(t),$$

where $P_{qk} \in [0, P_0]$ is the power of the $q$th LED allocated to transmitting the data of user $k$. Assuming a total radiation power limit of $P_0$ for each LED, which is the maximum optical power radiated from each LED, the constraint $\sum_{k=1}^{K} P_{qk} \leq P_0$ needs to be applied to the allocated powers. Since the power of light is nonnegative, we also require that $P_{qk} \geq 0, \forall q$. These power levels are organized in a $Q \times K$ matrix denoted as $P$. After the channel, the signal received by the $v$th detector of user $k$ can be written as

$$r_{kv}(t) = \sum_{q=1}^{Q} h_{qkv} x_q(t) + n_{kv}(t), \quad k = 1, \ldots, K$$

where $n_{kv}(t)$ is the white noise added to the $v$th detector of user $k$. Thus, the signal received by user $k$ should be an linear combination of the signal from each detector, which can be represented as

$$R_{k}(t) = \sum_{v=1}^{V} \mu_{kv} r_{kv}(t),$$

where $\mu_{kv} \in [0, 1]$ is the combination weight of the $v$th detector for user $k$. After sampling and MMSE filter, the signal for user $k$ can be written in matrix form as

$$y_k = d^T \hat{B}_k C w_k + n_k^T w_k,$$

where $d$ is the data vector, $d = (d(1), d(2), \ldots, d(K))^T$. We define the intended data for each user to be a binary data stream, i.e., $d(k) \in \{0, 1\}$. The noise vector is $n_k$, which is a linear combination of white noise, thus has variance $\sigma^2(\sum_v \mu_{kv}^2)$, and the MMSE filter for user $k$ is defined as $w_k$. $C$ represents the CDMA code matrix, which can be represented as $C = (c_1, c_2, \ldots, c_K)^T$, where $c_k$ is the CDMA code for user $k$. To facilitate the formulation, we define $\hat{B}_k = \text{diag}((H_{k}, u_k)^T P)$, where $u_k = (\mu_{k1}, \mu_{k2}, \ldots, \mu_{KV})^T$ and

$$H_k = \begin{pmatrix}
h_{1k1} & h_{1k2} & \cdots & h_{1kV} \\
h_{2k1} & h_{2k2} & \cdots & h_{2kV} \\
\vdots & \vdots & \ddots & \vdots \\
h_{Qk1} & h_{Qk2} & \cdots & h_{QkV}
\end{pmatrix}.$$

### B. Joint Optimization

In this section, we describe the M-PAJO algorithm. The MMSE receiver is designed independently for each user. We define the mean-squared error $J_k$ for user $k$ as

$$J_k = E_{d,n} \{(d^T \hat{B}_k C w_k + n_k^T w_k - d_k)^2\},$$

where $E_{d,n}$ represents expectation with respect to the data vector $d$ and the noise $n_k$. Solving for $\frac{\partial J_k}{\partial w_k} = 0$, the MMSE linear receiver $w_k$ can be obtained as

$$w_k = \left(C^T \hat{B}_k \Sigma_d \hat{B}_k C + \sigma^2(\sum_v \mu_{kv}^2) I\right)^{-1} C^T \hat{B}_k q_k,$$

where $\Sigma_d = E\{d^T d\}$ is the covariance matrix for the data, $q_k = E\{d \cdot d_k\}$ is the identity matrix. The SINR for user $k$ can thus be written as [4]

$$\text{SINR}_k = \frac{w_k^T C^T \hat{B}_k \Sigma_d \hat{B}_k C w_k + \sigma^2(\sum_v \mu_{kv}^2) w_k^T w_k}{\frac{w_k^T C^T \hat{B}_k \Sigma_d \hat{B}_k C w_k}{w_k^T C^T \hat{B}_k A_k \Sigma_d A_k \hat{B}_k^T C w_k + \sigma^2(\sum_v \mu_{kv}^2) w_k^T w_k},$$

where $\hat{E}_k$ is defined as a matrix with a 1 in its $(k, k)$th element and zeros in all other places, and $A_k = I - \hat{E}_k$.

Thus, after maximizing the minimum SINR among all the users, we can get the fair optimal power allocation and received signal combination scheme as

$$[P^*, M^*] = \arg \max_{P, M} \min_k \text{SINR}_k,$$

where $M = (u_1, u_2, \ldots, u_K)$, $P^*$ and $M^*$ are the optimal power allocation and receiver weights, respectively.

### III. Numerical Results

The parameters used to obtain the numerical results are shown in Tables I. Fig. 3 shows the geometric position of the lamps and users within the indoor environment.

The BER of the proposed M-PAJO with 4-detector and 7-detector is shown in Fig. 4, where we compare the per-
performance of the M-PAJO and PAJO. “EP” represents equal power allocation with optimized received signal combination case. “EW” represents equal weighted signal combination with optimized power allocation case ($\mu_{kv} = 1$). From the simulation results, the proposed M-PAJO has better BER performance than EP, EW and PAJO algorithms.

Fig. 5 shows the BER performance of M-PAJO with different receiver inclination angles from 20 degrees to 60 degrees. We simulated 5 trials of 4 users random distributed in the indoor environment. From the results, the FOV impacts the BER performance more than the inclination angles. In general, with the help of our proposed algorithm, the larger the FOV the better the BER performance for M-PAJO. In addition, the 7-detector M-PAJO is always superior to the 4-detector one.

Fig. 6 shows that when the number of users increases (selected in the order shown in Fig. 3), the BER performances of PAJO and M-PAJO become worse, due to an increase in MAI. Again the 7-detector M-PAJO has better BER performance than the 4-detector case.

To analyze the performance of the proposed M-PAJO from a statistical point of view, we simulate 40 trials of 4 users randomly distributed in the indoor environment. The simulation results are shown in Fig. 7. For a peak radiation power to noise ratio of 51 dB, more than 75% of the 160 users’ BER for both the 4-detector and 7-detector cases are lower than $10^{-3}$.

IV. Conclusion

In this paper, we present an optimal power allocation and received signal combination scheme for indoor VLC systems. With the help of multiple photodetectors for each user, our proposed M-PAJO has more than 3 dB power advantage compared with the single-detector algorithm.

References