Multi-User MIMO–OFDM for Indoor Visible Light Communication Systems

Qi Wang¹, Zhaocheng Wang¹, Chen Qian¹, Linglong Dai¹, and Jinguo Quan²

¹Department of Electronic Engineering, Tsinghua University, Beijing, China
²Shenzhen Graduate School, Tsinghua University, Shenzhen, China
Visible light communication

Advantages
- No electromagnetic interference
- High security
- Low cost

Multiple LED units are usually installed in a single room
- Provide sufficient illumination
- Bandwidth of off-the-shelf LED is limited
- MIMO can be naturally used to boost the data rate
Multiuser MIMO VLC

- Precoding
  - Zero forcing
  - Dirty paper coding
  - Minimum mean-squared error (MMSE)
  - Block diagonalization
- OFDM → High spectral efficiency
- MIMO–OFDM
System Model

- $N_t$ LED units
- $N_r$ users with single PD
System Model

- DC channel gain
  \[ h_{p,q}^{DC} = \begin{cases} \frac{\rho_p A_p}{d_{p,q}^2} R(\phi_q) \cos(\varphi_{p,q}), & \varphi_{p,q} \leq \Psi_{c,p} \\ 0, & \varphi_{p,q} > \Psi_{c,p} \end{cases} \]
  - \( \rho_p \): responsivity coefficient of PD
  - \( d_{p,q} \): distance between the qth LED unit and the pth user
  - \( \varphi_{p,q} \): incidence angle of the light
  - \( \Psi_{c,p} \): receiver FOV

- Noise
  \[ \sigma_p^2 = 2eP_p B + 2e\rho_p \chi_{amb} A_p \left(1 - \cos(\Psi_{c,p})\right)B + i_{amp}^2 \]
  - \( P_p \): the average received optical power at the pth user
In existing MU–MIMO VLC systems, single-carrier modulations are utilized

- Time domain precoding
- Distances of the multiple transmitter–receiver links are different $\rightarrow$ different delays

$$h_{p,q}(t) = h_{p,q}^{DC} \delta\left(t - \frac{d_{p,q}}{c}\right)$$

- Frequency-domain channel response

$$H_{p,q,k} = h_{p,q}^{DC} \exp\left(-\frac{j2\pi k B d_{p,q}}{Nc}\right)$$
Precoding is performed on each subcarrier to eliminate multiuser interference

- Data: $D_{p,k}, D_{p,k} = D^*_{p,N-k}$
- Precoding weights: $W_{p,q,k}$
- Frequency-domain signal: $X_{q,k} = \sum_{p=1}^{N_r} W_{p,q,k} D_{p,k}, k = 0, 1, \ldots, N-1$

After IFFT

$$x_{q,n} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_{q,n} \exp\left( j \frac{2\pi}{N} nk \right), n = 0, 1, \ldots, N-1$$

CP is added to eliminate ISI
Precoding Design

- At the receiver of the pth user

\[ R_{p,k} = \sum_{q=1}^{N_t} H_{p,q,k} X_{q,k} + Z_{p,k} = H_{p,k}^T W_{p,k} D_{p,k} + \sum_{l \neq p}^{N_t} H_{l,k}^T W_{l,k} D_{l,k} + Z_{p,k} \]

- Rewrite in the matrix form

\[ R_{p,k} = \sum_{q=1}^{N_t} H_{p,q,k} X_{q,k} + Z_{p,k} = H_{p,k}^T W_{p,k} D_{p,k} + \sum_{l \neq p}^{N_t} H_{l,k}^T W_{l,k} D_{l,k} + Z_{p,k} \]

- Two simple precoding methods
  - Zero-forcing
    \[ H_k W_k = \text{diag}(\lambda_k) \]
    \[ W_k = H_k^\dagger \text{diag}(\lambda_k) = H_k^H \left( H_k H_k^H \right)^{-1} \text{diag}(\lambda_k) \]
  - MMSE
    \[ W_k = H_k^H \left( H_k H_k^H + \text{diag}(\sigma_{z_k}^2) \right)^{-1} \text{diag}(\lambda_k) \]
Intensity modulation with direct detection
Non-negative real signals are transmitted
DC bias is added $\rightarrow$ DCO-OFDM

$$\bar{P}_{DC,q} = \eta \sqrt{E\{x_{q,n}^2\}}$$

Low DC bias $\rightarrow$ clipping distortion
High DC bias $\rightarrow$ inefficient in terms of power
Define a minimum DC bias ratio $\eta_0$ to avoid clipping distortion
Average optical power: $P$
Minimum DC bias scheme
- Each transmitter uses different DC biases
  \[ P_{DC,q} = \eta_0 \sqrt{E\{x_{q,n}^2\}} \]
- Optical power:
  \[ P_{opt,q} = E\{x_{q,n} + P_{DC,q}\} = E\{x_{q,n}\} + P_{DC,q} = \bar{P}_{DC,q} \]
  \[ y_{q,n} = \alpha (x_{q,n} + \bar{P}_{DC,q}) \]
- Scaling factor:
  \[ \alpha = \frac{N_t P}{\eta_0 \sum_{q=1}^{N_t} \sqrt{E\{x_{q,n}^2\}}} \]
- DC bias:
  \[ P_{DC,q} = \alpha \bar{P}_{DC,q} = \sqrt{E\{x_{q,n}^2\}} N_t P / \sum_{q=1}^{N_t} \sqrt{E\{x_{q,n}^2\}} \]

Unified DC bias scheme
- Each transmitter uses the same DC bias
  \[ \alpha = \frac{P}{\eta_0 \sqrt{\max_{1 \leq q \leq N_t} E\{x_{q,n}^2\}}} \]
  \[ P_{DC,q} = P \]
ACO–OFDM–based MU–MIMO

- Only odd subcarriers are modulated
  \[ x_{q,n} = -x_{q,n+N/2}, n = 0, 1, \ldots, N - 1 \]
- Asymmetrically clipping at zero
- No DC bias: better performance?
- Optical power:
  \[ P_{opt,q} = E\{x_{q,n}^{(c)}\} = \sqrt{E\{x_{q,n}^2\}} / 2\pi \]
- Scaling factor:
  \[ \alpha = \frac{N_t P}{\sum_{q=1}^{N_t} P_{opt,q}} = \frac{N_t P}{\sum_{q=1}^{N_t} \sqrt{E\{x_{q,n}^2\}} / 2\pi} \]
## Simulation Results

### Simulation parameters for VLC system configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room size (length × width × height)</td>
<td>5 m × 5 m × 3 m</td>
</tr>
<tr>
<td>LED 1 coordinate</td>
<td>[1.25 1.25 3]</td>
</tr>
<tr>
<td>LED 2 coordinate</td>
<td>[1.25 3.75 3]</td>
</tr>
<tr>
<td>LED 3 coordinate</td>
<td>[3.75 1.25 3]</td>
</tr>
<tr>
<td>LED 4 coordinate</td>
<td>[3.75 3.75 3]</td>
</tr>
<tr>
<td>LED emission angle ( \phi_q )</td>
<td>60 deg</td>
</tr>
<tr>
<td>PD area ( A_{PD,p} )</td>
<td>1 cm²</td>
</tr>
<tr>
<td>PD responsivity coefficient ( \rho_p )</td>
<td>0.4 A/W</td>
</tr>
<tr>
<td>PD concentrator refractive index ( \gamma )</td>
<td>1.5</td>
</tr>
<tr>
<td>Lambertian emission mode number ( m )</td>
<td>1</td>
</tr>
<tr>
<td>Receiver FOV angle ( \Psi_{c,p} )</td>
<td>62 deg</td>
</tr>
<tr>
<td>Pre-amplifier noise density ( i_{amp} )</td>
<td>5 pA/Hz(^{-1} )</td>
</tr>
<tr>
<td>Ambient light photocurrent ( \chi_{amp} )</td>
<td>10.93 A/m(^2)/Sr</td>
</tr>
<tr>
<td>System bandwidth ( B )</td>
<td>1 GHz</td>
</tr>
<tr>
<td>OFDM subcarrier number ( N )</td>
<td>64</td>
</tr>
<tr>
<td>Cyclic prefix length ( N_{CP} )</td>
<td>3</td>
</tr>
</tbody>
</table>

### Case 1

- User 1: [2.5 2.5 0.85]
- User 2: [3.2 3.9 0.85]

### Case 2

- User 1: [2.05 1.6 0.85]
- User 2: [2.05 1.4 0.85]
Simulation Results

- Spectral efficiency of each subcarrier with the average emitted optical power $P=0 \, \text{dB}$
Simulation Results

DCO-OFDM-based MU-MIMO VLC

1. Case 1, ZF, Minimum DC Bias
2. Case 1, ZF, Unified DC Bias
3. Case 1, MMSE, Minimum DC Bias
4. Case 1, MMSE, Unified DC Bias
5. Case 2, ZF, Minimum DC Bias
6. Case 2, ZF, Unified DC Bias
7. Case 2, MMSE, Minimum DC Bias
8. Case 2, MMSE, Unified DC Bias

ACO-OFDM-based MU-MIMO VLC

1. Case 1, ZF, Minimum DC Bias
2. Case 1, ZF, ACO-OFDM
3. Case 2, ZF, Minimum DC Bias
4. Case 2, ZF, ACO-OFDM
Conclusions

- MU-MIMO-OFDM is investigated for indoor VLC systems
- The distance differences of the multiple transmitter-receiver links are considered
- DCO-OFDM with minimum and unified DC bias, and ACO-OFDM are compared in the proposed system
Thanks for your suggestions!