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

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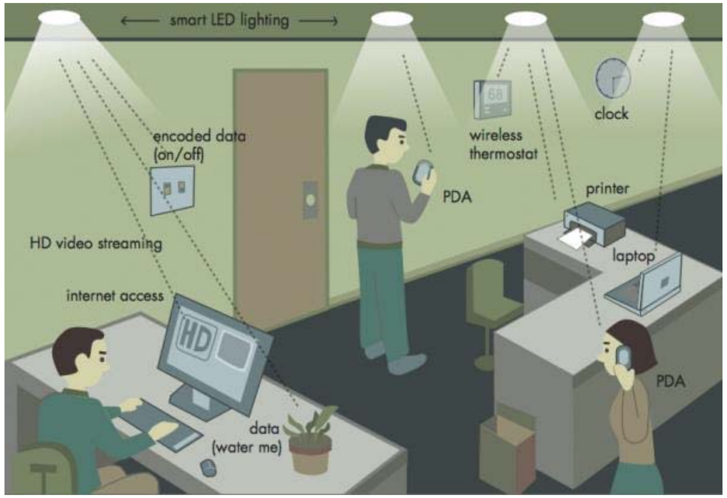
Contents

Visible light communication

- Advantages
  - No electromagnetic interference
  - High security
  - Low cost



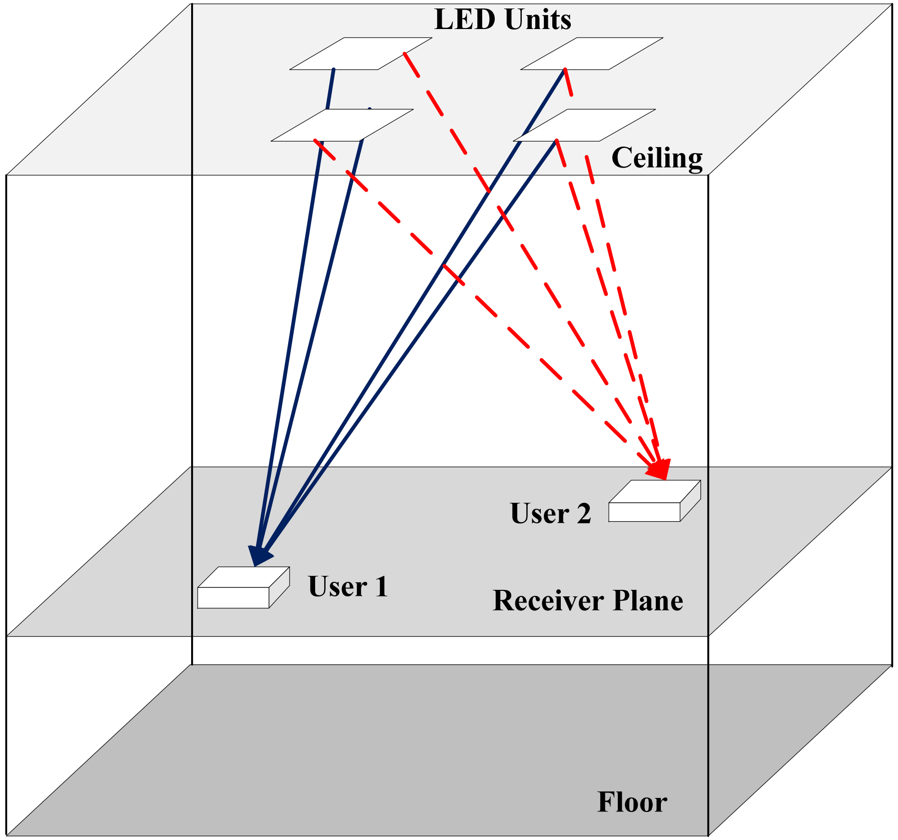
- Multiple LED units are usually installed in a single room
  - Provide sufficient illumination
  - Bandwidth of off-the-shelf LED is limited
  - MIMO can be naturally used to boost the data rate

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 $$h_{p,q}^{DC} = \begin{cases} \frac{\rho_p A_p}{d_{p,q}^2} R(\phi_q)\cos(\varphi_{p,q}), \varphi_{p,q} \le \Psi_{c,p} \\ 0, \varphi_{p,q} > \Psi_{c,p} \end{cases}$$
  - ρ_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

$$\sigma_p^2 = 2eP_pB + 2e\rho_p\chi_{amb}A_p\left(1-\cos\left(\Psi_{c,p}\right)\right)B + i_{amp}^2$$

  - P_p : the average received optical power at the pth user

MU-MIMO-OFDM for VLC

- In existing MU-MIMO VLC systems, single-carrier modulations are utilized
- Time domain precoding
- Distances of the multiple transmitter-receiver links are different → different delays

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

- Frequency-domain channel response

$$H_{p,q,k} = h_{p,q}^{DC}\exp\left(-\frac{j2\pi kBd_{p,q}}{Nc}\right)$$

- Complex-valued

MU-MIMO-OFDM for VLC

- 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 singal: $X_{q,k} = \sum_{p=1}^{N_r} W_{p,q,k} D_{p,k}, k = 0,1,\cdots,N-1$
- After IFFT

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

- CP is added to eliminate ISI

Precoding Design

- At the receiver of the pth user

$$R_{p,k} = \sum_{q=1}^{N_t} H_{p,q,k} X_{q,k} + Z_{p,k} = \mathbf{H}_{p,k}^T \mathbf{W}_{p,k} D_{p,k} + \sum_{l \neq p}^{N_t} \mathbf{H}_{l,k}^T \mathbf{W}_{l,k} D_{l,k} + Z_{p,k}$$

- Rewrite in the matrix form

$$R_{p,k} = \sum_{q=1}^{N_t} H_{p,q,k} X_{q,k} + Z_{p,k} = \mathbf{H}_{p,k}^T \mathbf{W}_{p,k} D_{p,k} + \sum_{l \neq p}^{N_t} \mathbf{H}_{l,k}^T \mathbf{W}_{l,k} D_{l,k} + Z_{p,k}$$

- Two simple precoding methods
  - Zero-forcing $\mathbf{H}_k \mathbf{W}_k = \mathrm{diag}\left(\boldsymbol{\lambda}_k\right)$

$$\mathbf{W}_k = \mathbf{H}_k^{\dagger} \mathrm{diag}\left(\boldsymbol{\lambda}_k\right) = \mathbf{H}_k^H \left(\mathbf{H}_k \mathbf{H}_k^H\right)^{-1} \mathrm{diag}\left(\boldsymbol{\lambda}_k\right)$$

  - MMSE

$$\mathbf{W}_k = \mathbf{H}_k^H \left(\mathbf{H}_k \mathbf{H}_k^H + \mathrm{diag}\left(\boldsymbol{\sigma}_{\mathbf{Z}_k}^2\right)\right)^{-1} \mathrm{diag}\left(\boldsymbol{\lambda}_k\right)$$

DCO-OFDM-based MU-MIMO

- Intensity modulation with direct detection
- Non-negative real signals are transmitted
- DC bias is added → DCO-OFDM

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

- Low DC bias → clipping distortion
- High DC bias → inefficient in terms of power
- Define a minimum DC bias ratio η_0 to avoid clipping distortion
- Average optical power: P

DCO-OFDM-based MU-MIMO

- Minimum DC bias scheme
  - Each transmitter use different DC biases

$$\bar{P}_{DC,q} = \eta_0 \sqrt{E\left\{x_{q,n}^2\right\}}$$

  - Optical power: $P_{opt,q} = E\left\{x_{q,n} + \bar{P}_{DC,q}\right\} = E\left\{x_{q,n}\right\} + \bar{P}_{DC,q} = \bar{P}_{DC,q}$

$$y_{q,n} = \alpha\left(x_{q,n} + \bar{P}_{DC,q}\right)$$

  - Scaling factor: $\alpha = N_t P \Big/ \eta_0 \sum_{q=1}^{N_t} \sqrt{E\left\{x_{q,n}^2\right\}}$
  - DC bias: $P_{DC,q} = \alpha \bar{P}_{DC,q} = \sqrt{E\left\{x_{q,n}^2\right\}} N_t P \Big/ \sum_{q=1}^{N_t} \sqrt{E\left\{x_{q,n}^2\right\}}$
- Unified DC bias scheme
  - Each transmitter use the same DC bias

$$\alpha = \frac{P}{\eta_0 \sqrt{\max\limits_{1 \le q \le N_t} E\left\{x_{q,n}^2\right\}}} \qquad P_{DC,q} = P$$

ACO-OFDM-based MU-MIMO

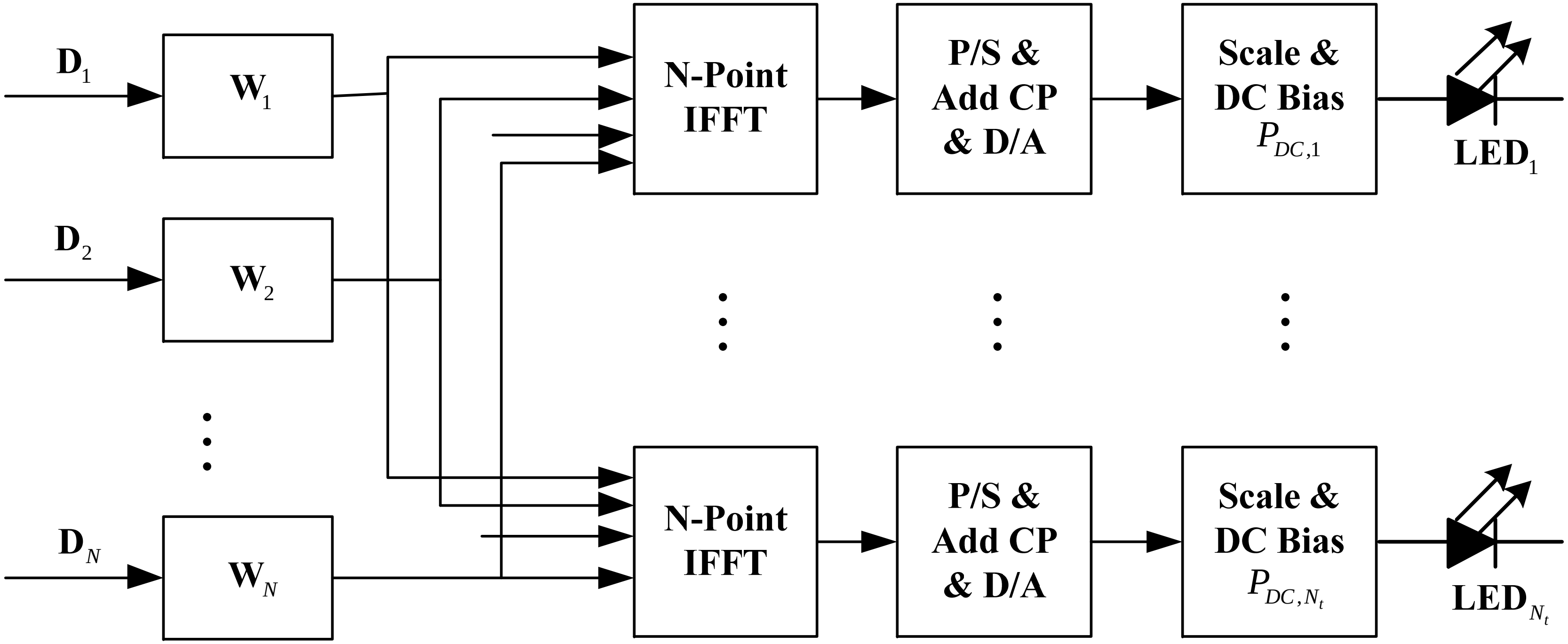
- Only odd subcarriers are modulated

$$x_{q,n} = -x_{q,n+N/2}, n = 0,1,\cdots,N-1$$

- Asymmetrically clipping at zero
- No DC bias: better performance?
- Optical power: $P_{opt,q} = E\left\{x_{q,n}^{(c)}\right\} = \sqrt{E\left\{x_{q,n}^{2}\right\}/2\pi}$
- Scaling factor:

$$\alpha = \frac{N_t P}{\sum_{q=1}^{N_t} P_{opt,q}} = \frac{N_t P}{\sum_{q=1}^{N_t} \sqrt{E\left\{x_{q,n}^{2}\right\}/2\pi}}$$

System Block Diagam



D_1

W_1

D_2

W_2

D_N

W_N

N-Point IFFT

P/S & Add CP & D/A

Scale & DC Bias $P_{DC,1}$

LED_1

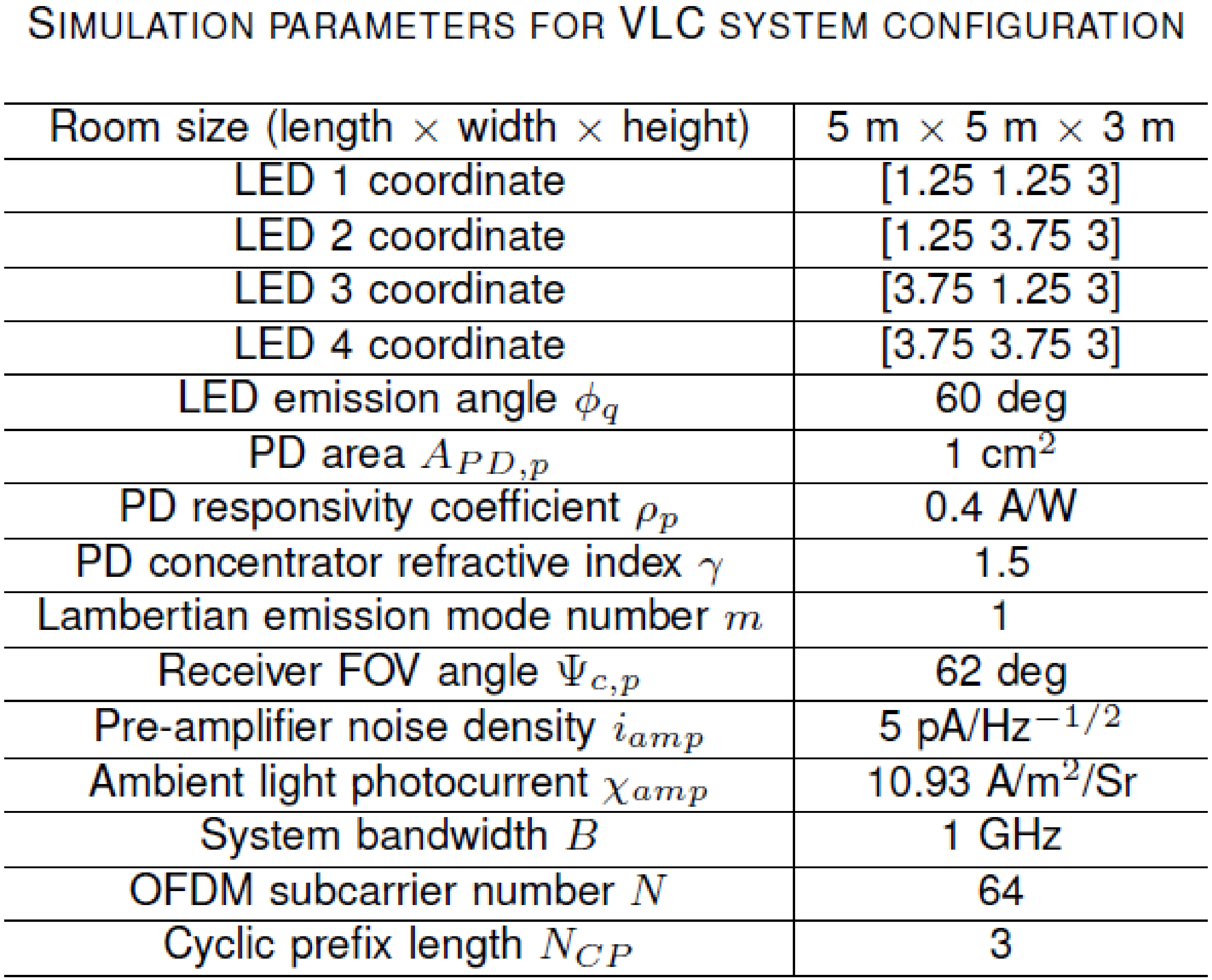
N-Point IFFT

P/S & Add CP & D/A

Scale & DC Bias P_{DC,N_t}

LED_{N_t}

Simulation Results



SIMULATION PARAMETERS FOR VLC SYSTEM CONFIGURATION

Room size (length × width × height)	5 m × 5 m × 3 m
LED 1 coordinate	[1.25 1.25 3]
LED 2 coordinate	[1.25 3.75 3]
LED 3 coordinate	[3.75 1.25 3]
LED 4 coordinate	[3.75 3.75 3]
LED emission angle ϕ_q	60 deg
PD area $A_{PD,p}$	1 cm^2
PD responsivity coefficient ρ_p	0.4 A/W
PD concentrator refractive index γ	1.5
Lambertian emission mode number m	1
Receiver FOV angle $\Psi_{c,p}$	62 deg
Pre-amplifier noise density i_{amp}	5 pA/Hz$^{-1/2}$
Ambient light photocurrent χ_{amp}	10.93 A/m^2/Sr
System bandwidth B	1 GHz
OFDM subcarrier number N	64
Cyclic prefix length N_{CP}	3

Case 1

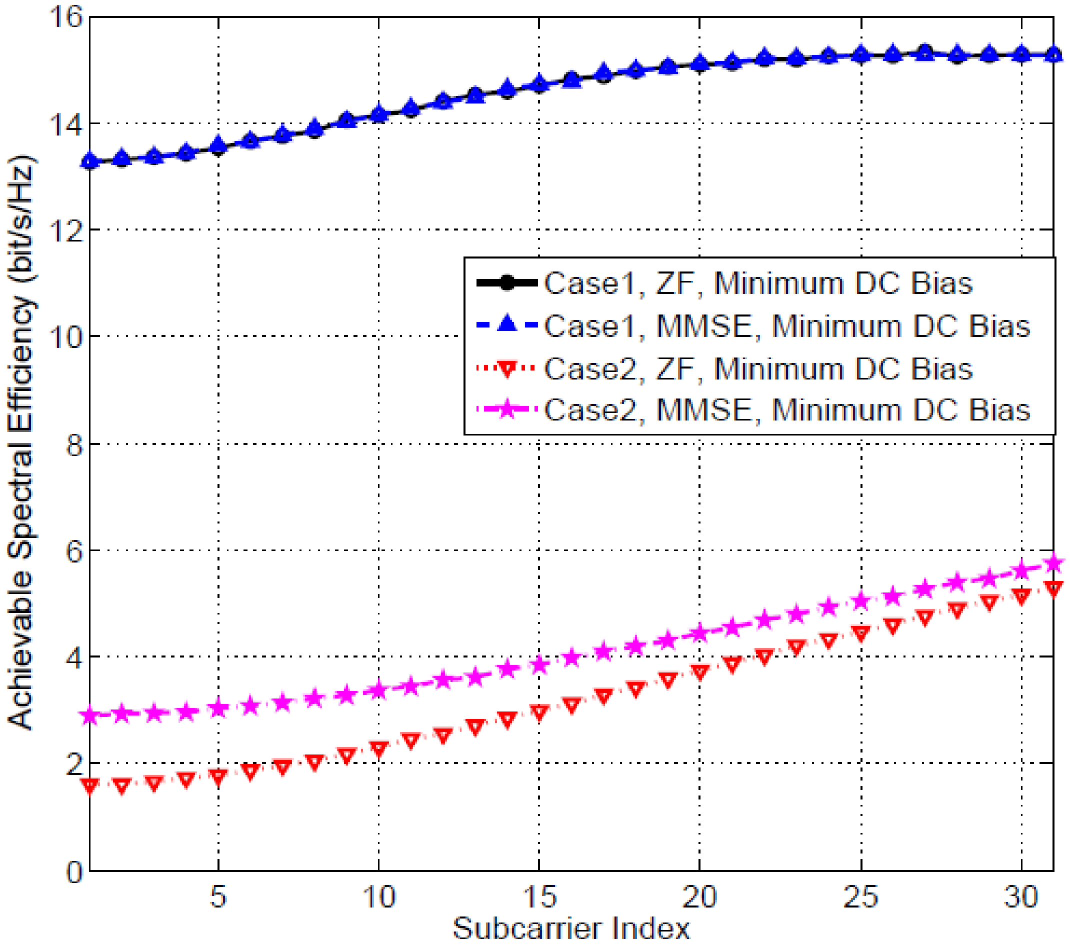
- User 1: [2.5 2.5 0.85]
- User 2: [3.2 3.9 0.85]

Case 2:

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

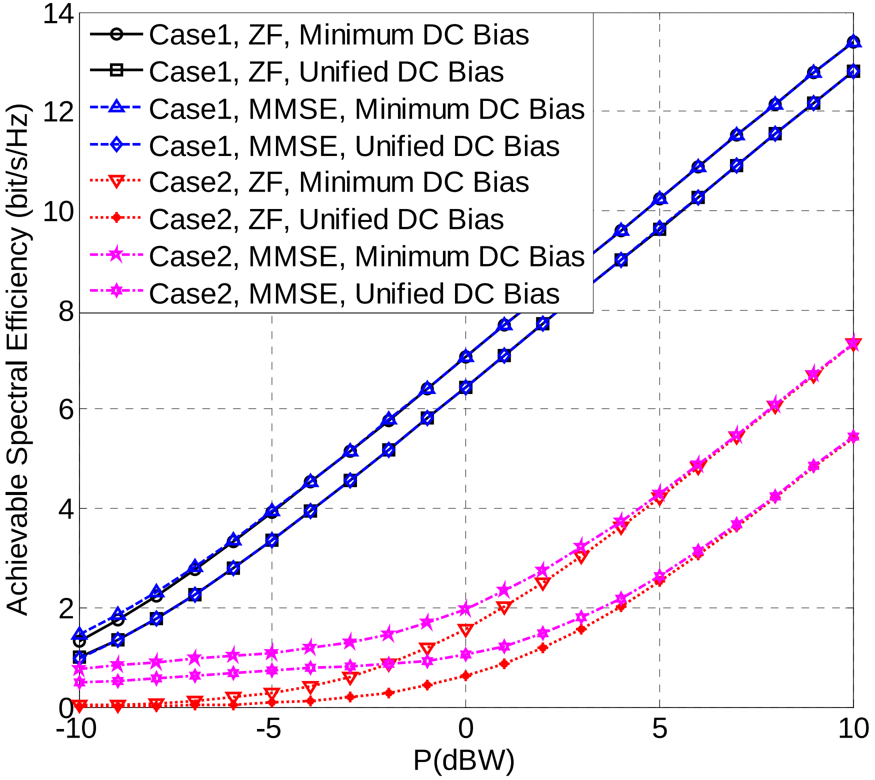
Simulation Results

- Spectral efficiency of each subcarrier with the average emitted optical power P=0 dB

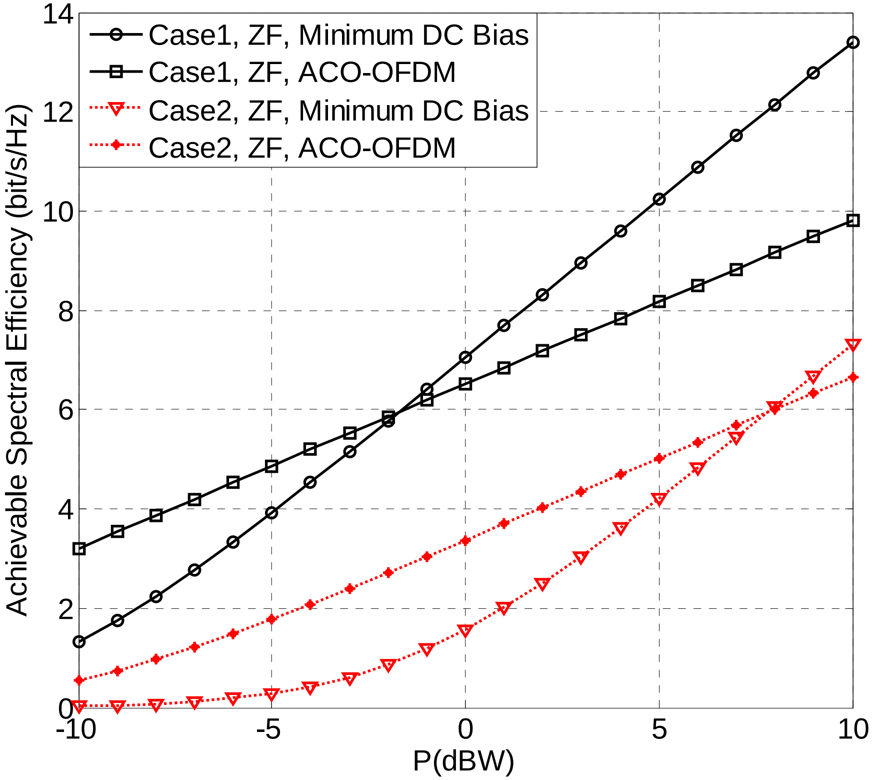


Simulation Results

DCO-OFDM-based MU-MIMO VLC



ACO-OFDM-based MU-MIMO VLC



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!