Joint Probabilistic Shaping and Precoding Design for MU-MISO VLC Systems

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- Visible light communication (VLC)
- Multi-user Multiple-Input Single Output VLC system
- Precoding Design
- Probabilistic Constellation Shaping

Backgrounds

❑ Visible light communication (VLC)

❖ Dual functionality
  - Illumination (primary)
  - Communication (secondary)

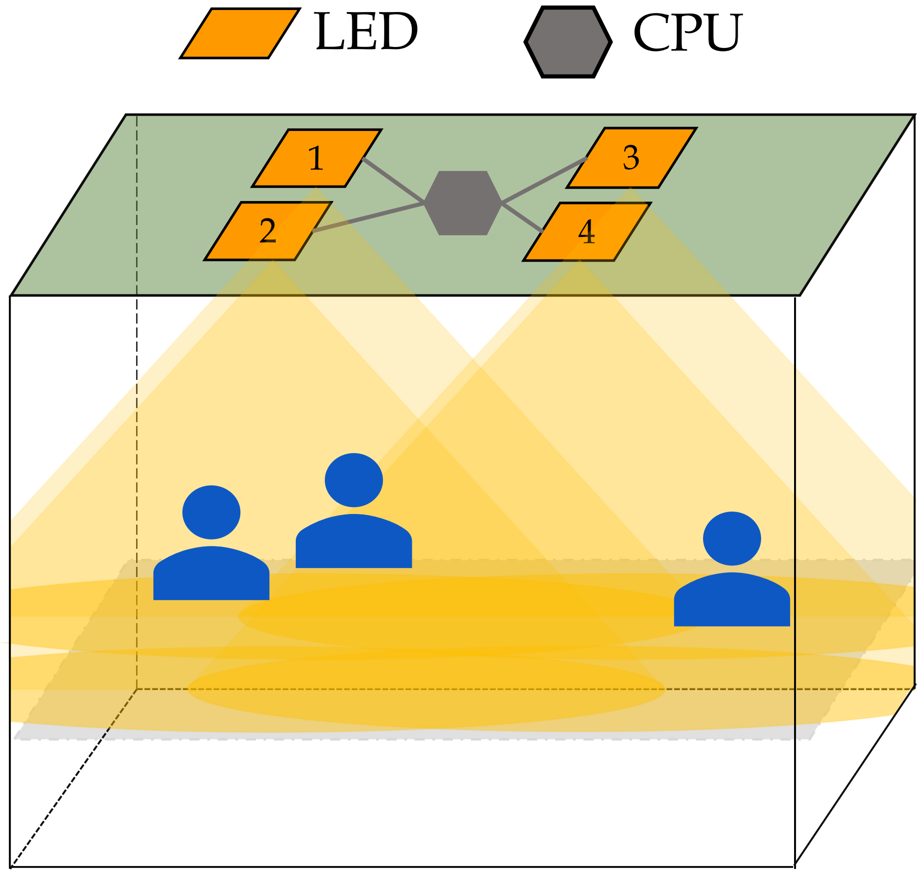
❖ Immunity to interference from other electromagnetic sources

❖ Environment friendly
  - Hospital
  - Airplane

VLC network is expected to support multiple mobile users

Backgrounds

❑ Multi-user Multiple Input Single Output VLC system (MU-MISO VLC)



- N_T LEDs simultaneously serve K users
- Each user is equipped with a single-photodiode (PD) receiver

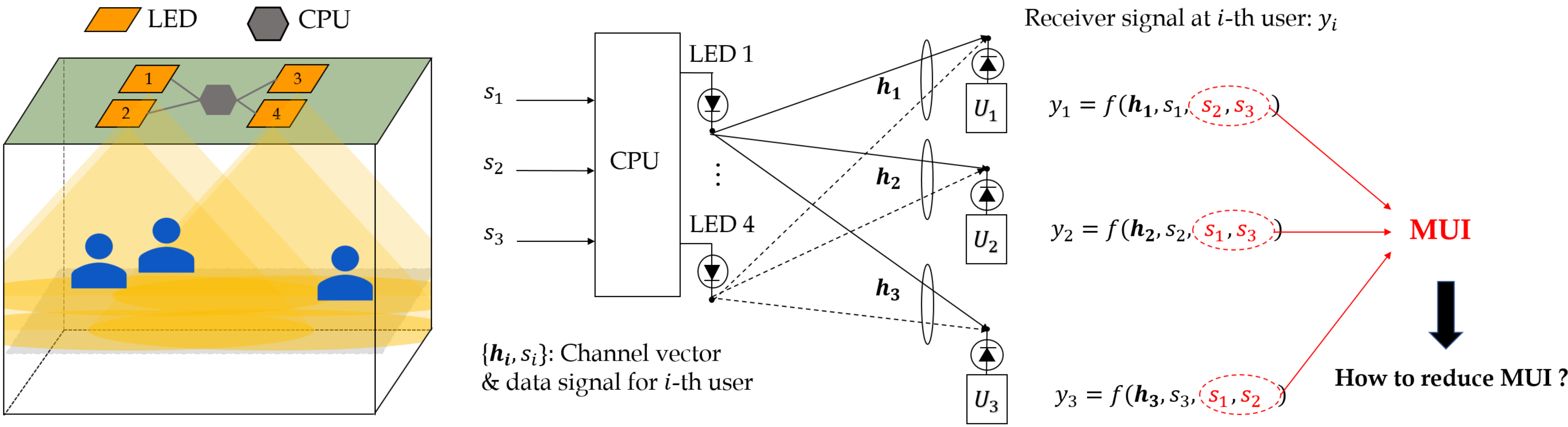
A multi-user multiple input single output (MU-MISO) VLC broadcast system

Drawbacks:

- Multi-user interference (MUI)
- Optical power constraint (peak and average)

Backgrounds

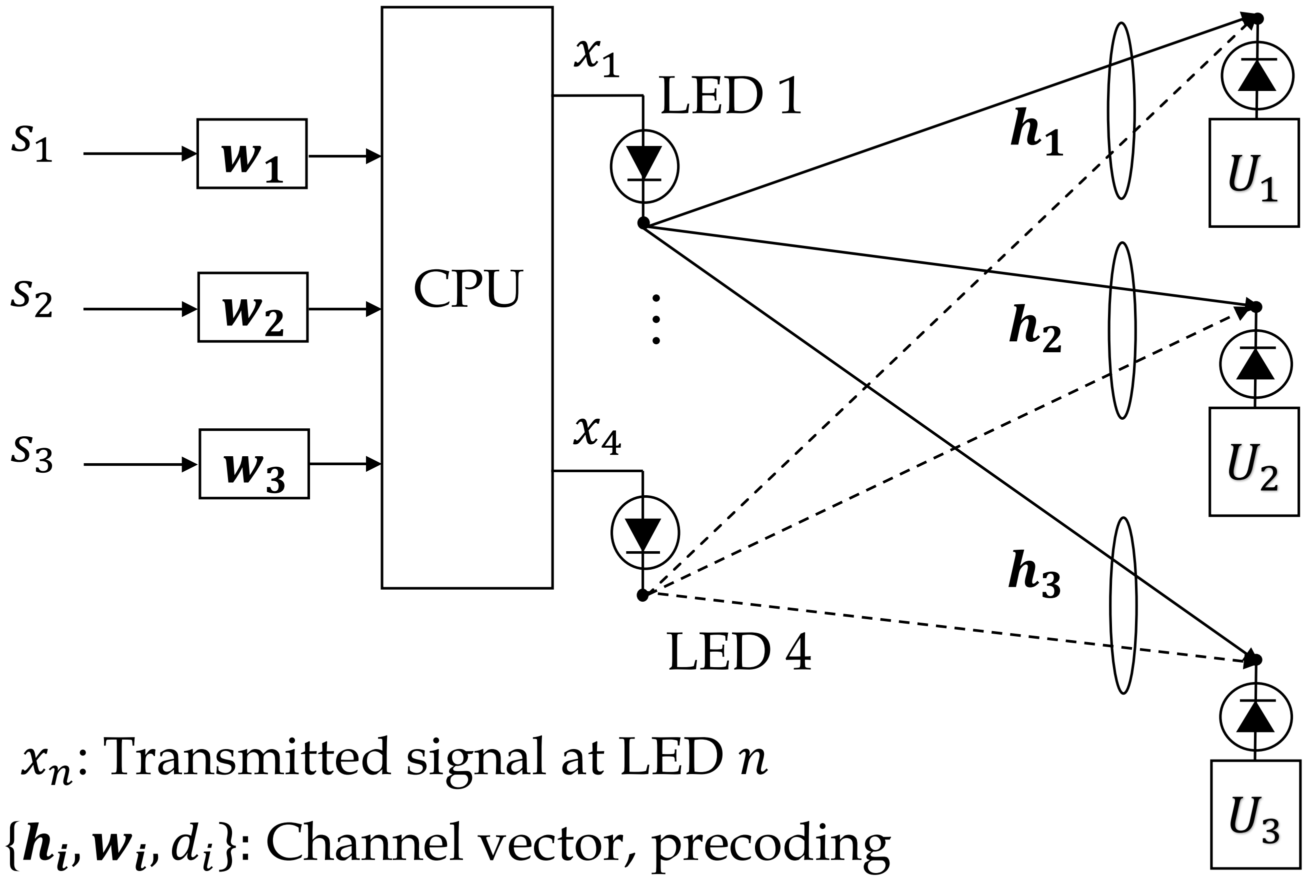
- **Multi-user interference (MUI)**



Backgrounds

❑ Precoding design

Linearly encoding s_i by a vector $\boldsymbol{w_i}$ to reduce the effect of multi-user interference at received signal



x_n: Transmitted signal at LED n

$\{\boldsymbol{h_i}, \boldsymbol{w_i}, d_i\}$: Channel vector, precoding vector & data signal for i-th user

❑ Received signal at the i-th user

$$y_i = \boldsymbol{h_i}\boldsymbol{w_i}s_i + \boldsymbol{h_i}\sum_{j=1, j\neq i}^{K} \boldsymbol{w_j}s_j + n_i$$

Multi-user interference (MUI)

❑ By generate precoding vector $\boldsymbol{w}$ based on the channel state information, MUI can be eliminated

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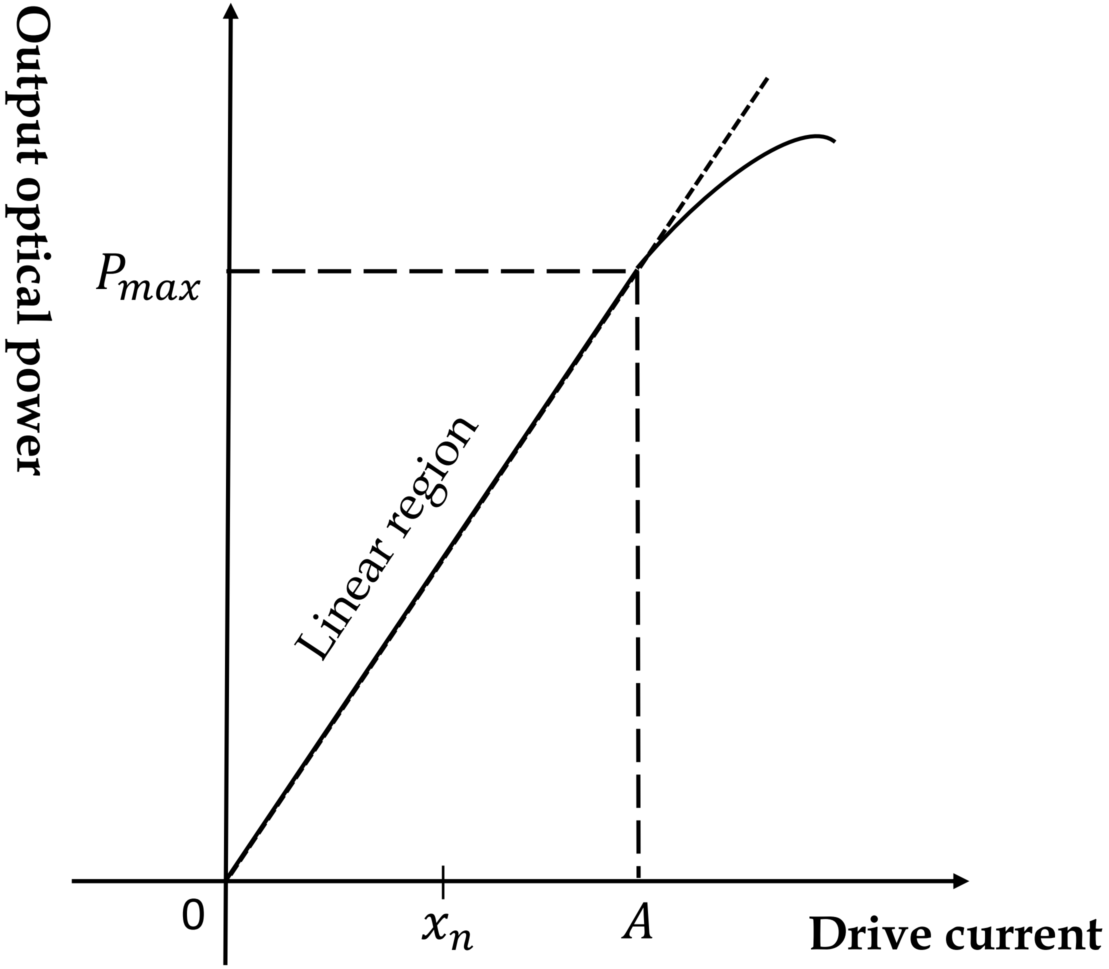
- **Optical power constraint**



❖ Peak power (amplitude) constraint:

$$0 \leq x_n \leq A$$

❖ Average power (amplitude) constraint:

$$\sum_{n=1}^{N_t} E[x_n] \leq \mathcal{E}$$

➡ Limit the sum rate of MU-MISO VLC system

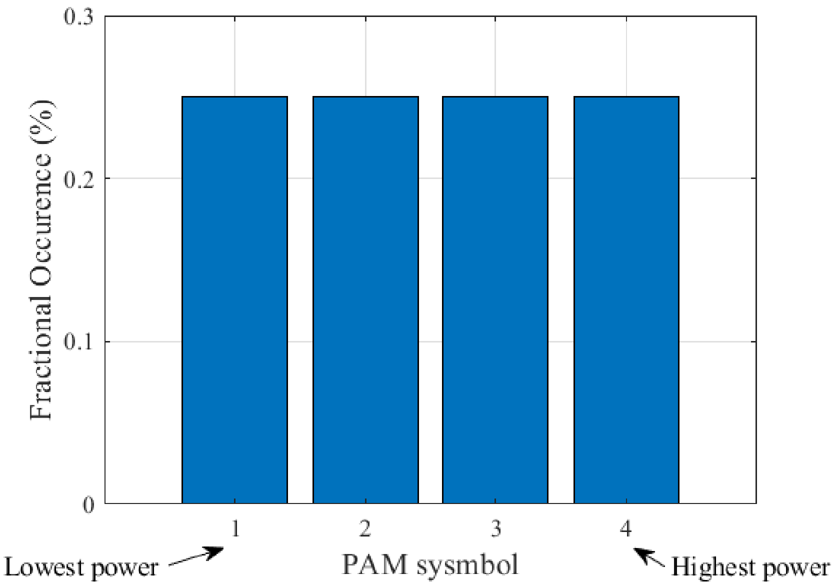
Backgrounds

❑ Probabilistic constellation shaping (PCS)

PCS is an approach to enhance the sum rate under power constraints

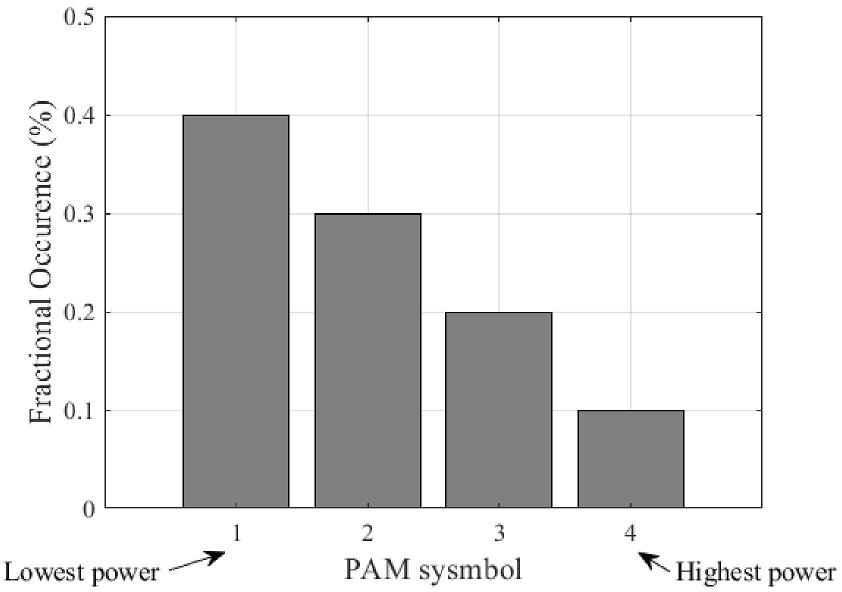
Standard transmission

- Each symbol transmitted with equal probability



Shaped transmission

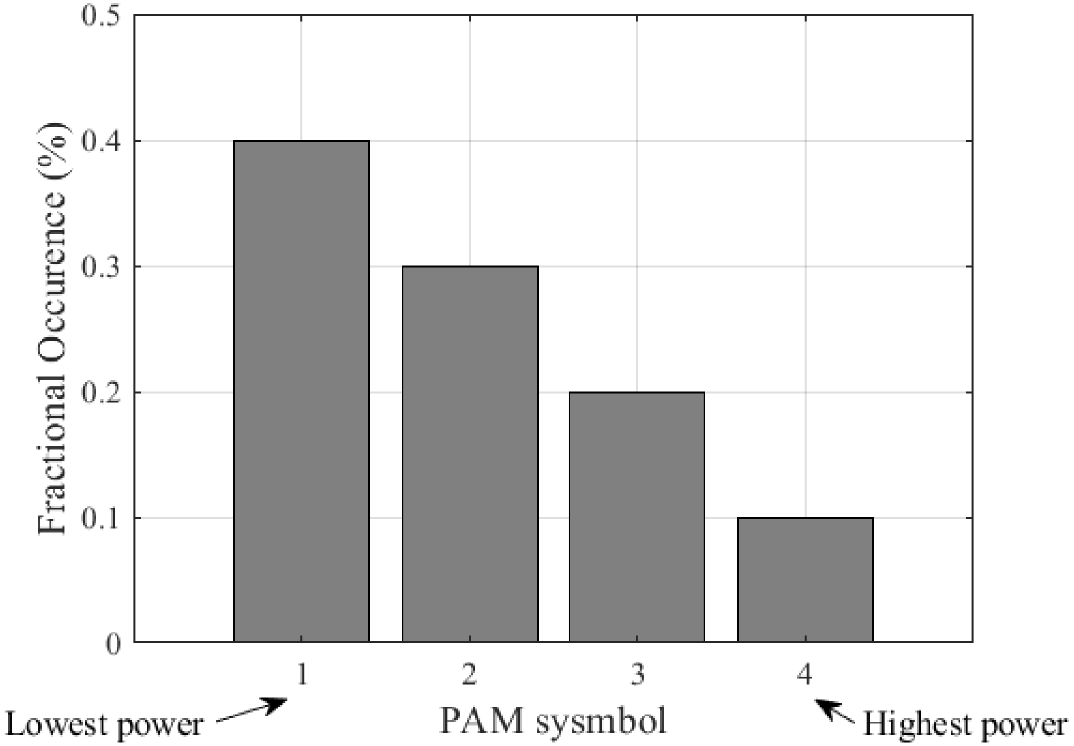
- Each symbol transmitted with different probability
- Higher power symbols transmitted less frequently



Backgrounds

❑ Probabilistic constellation shaping (PCS)

- Each symbol transmitted with different probability
- Higher power symbols transmitted less frequently



✓ Average power decreases

✓ Reduce non-linear effects in LEDs

➡ Improve the system's sum rate under the power constraints

Related works

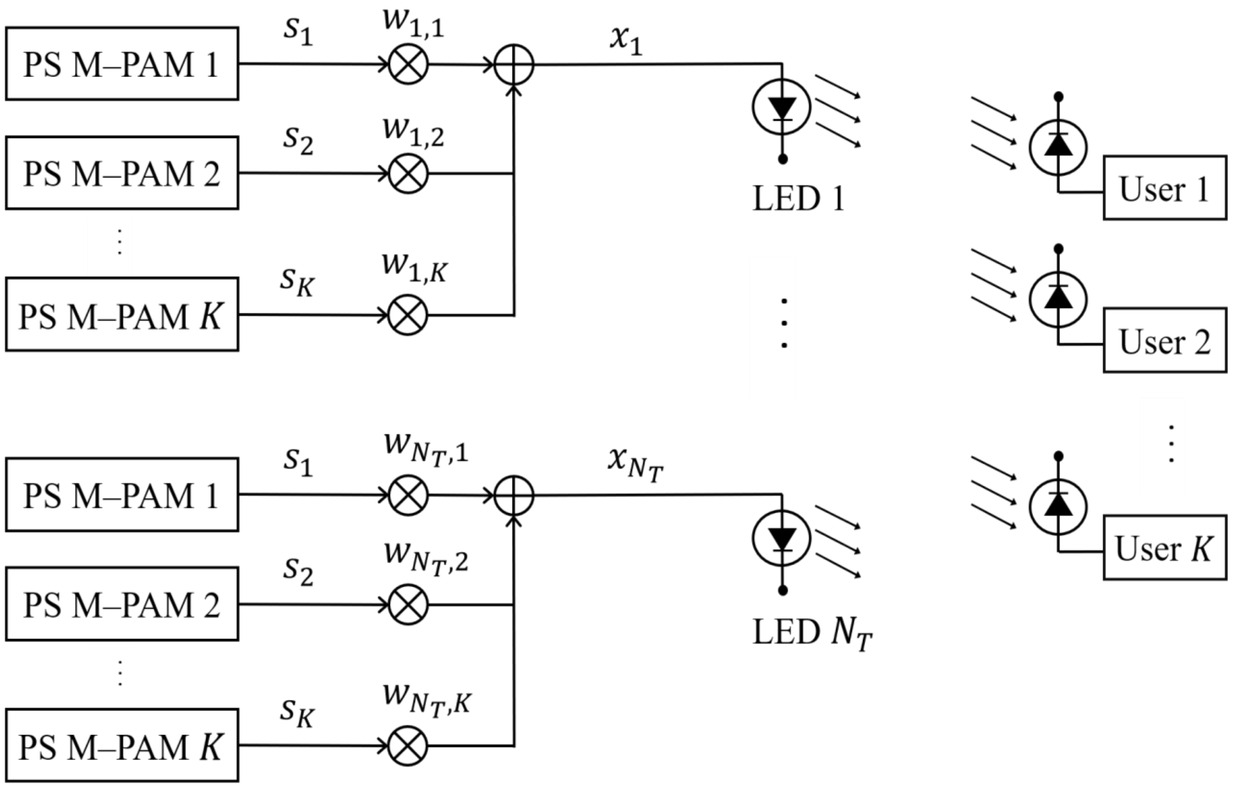
Reference	Main Contributions
[1] - 2022	Propose joint design of probabilistic M-PAM shaping and precoding to optimize the channel capacity of the MISO-VLC system with one user
[2] - 2022	Propose a novel adaptive coded spatial modulation scheme with probabilistic M-PAM shaping to improve the spectral efficiency of the MISO-VLC system with one user

➡ A design of probabilistic shaping and precoding for multi-user VLC systems is still missing

[1] F. Yang and Y. Dong, "Joint Probabilistic Shaping and Beamforming Scheme for MISO VLC Systems," in IEEE Wireless Communications Letters, vol. 11, no. 3, pp. 508-512, March 2022, doi: 10.1109/LWC.2021.3134268.
[2] A. Kafizov, A. Elzanaty and M. -S. Alouini, "Probabilistic Shaping-Based Spatial Modulation for Spectral-Efficient VLC," in IEEE Transactions on Wireless Communications, vol. 21, no. 10, pp. 8259-8275, Oct. 2022, doi: 10.1109/TWC.2022.3164991.

Research proposal- System model

❑ MU-MISO VLC system with PCS



- $\boldsymbol{s} = [s_1 \quad s_2 \cdots \quad s_K]$: vector of data symbols for K users
- $s_k \sim \{s_{k,m_k}\}$: data symbol for user k, drawn from the PS M-PAM k

$$k \in \{1, 2, \ldots, K\}, m_k \in \{1, 2, \ldots, M\}$$

- $\boldsymbol{w}_k = [w_{k,1} \quad w_{k,2} \cdots \quad w_{k,N_T}]$ is the precoding vector for user k-th user

Research proposal- System model

❑ Probabilistic shaping M-PAM k

With $k \in \{1, 2, \dots, K\}, m_k \ \in \{1, 2, \dots, M\}$),

$s_k \sim \{s_{k,m_k}\}$: s_k is a data symbol drawn from the PS M-PAM k with an amplitude a_{k,m_k} and the corresponding probability p_{k,m_k}.

PS M–PAM k

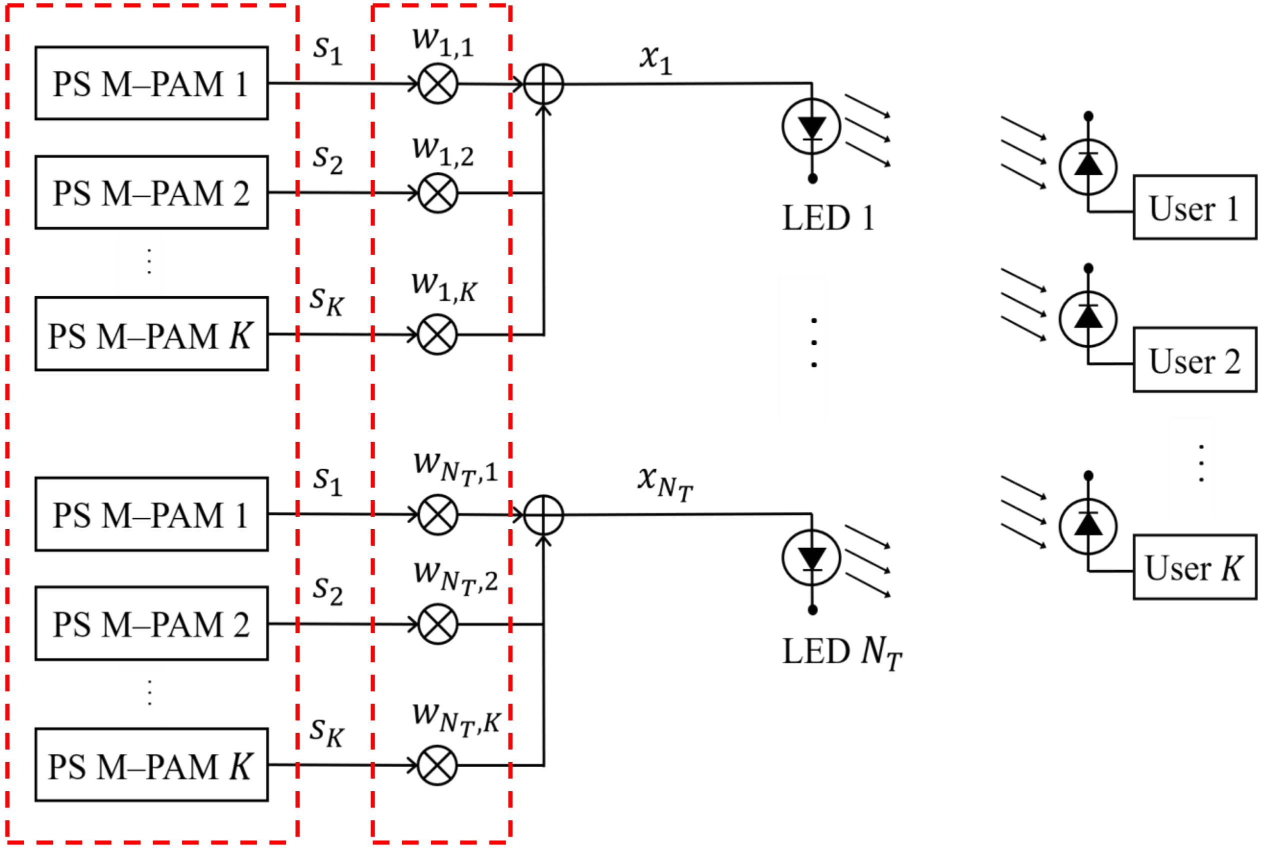
→ Amplitude vector: $\boldsymbol{a_k} = [a_{k,1} \quad a_{k,2} \cdots \quad a_{k,M}]$

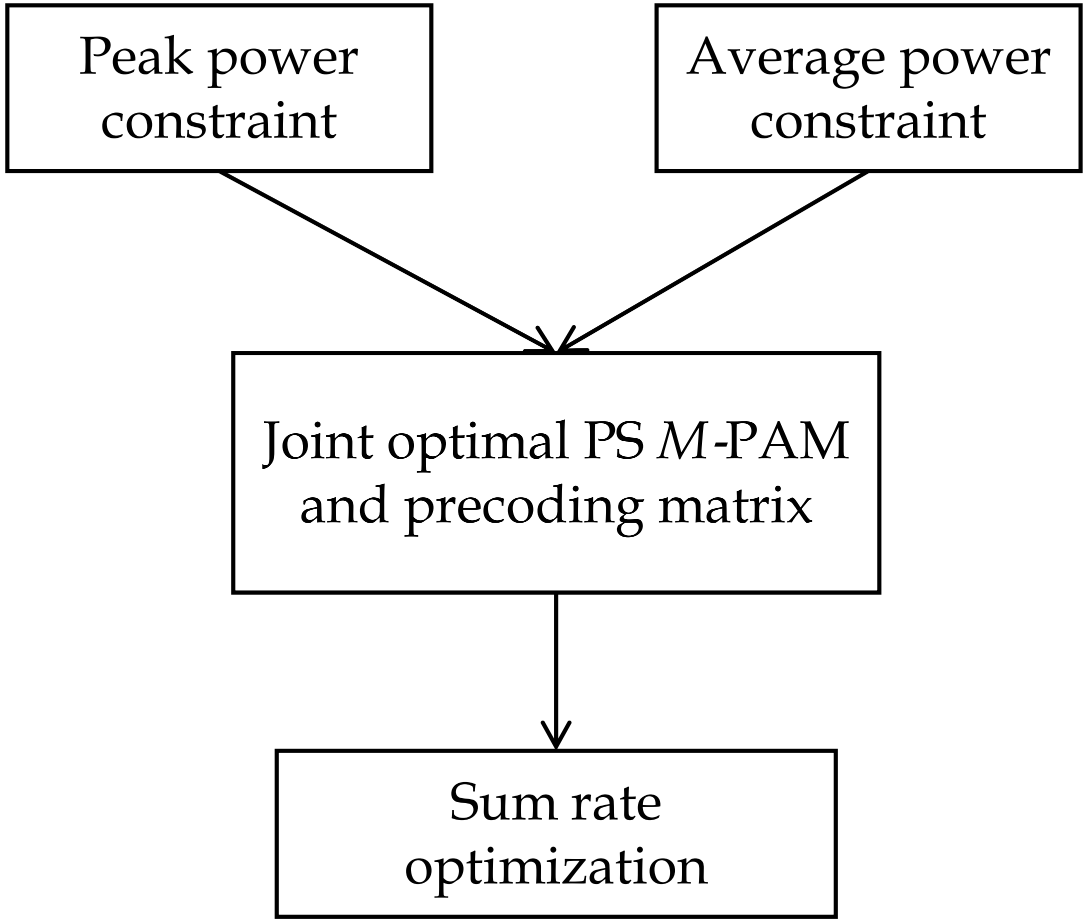
→ Fixed value based on LED's peak power

→ Probability mass function vector: $\boldsymbol{p_k} = [p_{k,1} \quad p_{k,2} \cdots \quad p_{k,M}]$

→ $\boldsymbol{p_k}$ can be optimized to improve the sum-rate performance

Research proposal - Goal





Our approach

- Problem formulate

$$\mathbb{P}1: \underset{\mathbf{P},\mathbf{W}}{\text{maximize}} \quad \sum_{k=1}^{K} R_k(\mathbf{P},\mathbf{W})$$ → Sum rate maximization

subject to

$$\sum_{k=1}^{K} \mathbf{a}_k^T \mathbf{p}_k \mathbb{1}_{N_T\times 1}^T \mathbf{w}_k \leq \mathcal{E},$$ → Average power constraint

$$\left\| [\mathbf{W}]_{n,:} \right\|_1 \leq 1, \ \forall n \in \{1, 2, \cdots, N_T\},$$ → Peak power constraint

$$\mathbf{0}_{K\times M} \leq \mathbf{P} \leq \mathbb{1}_{K\times M},$$

$$\mathbf{P} \times \mathbb{1}_{M\times 1} = \mathbb{1}_{K\times 1},$$

- $\mathbf{P} = [\boldsymbol{p}_1 \ \ \boldsymbol{p}_2 \cdots \ \boldsymbol{p}_K]$: PMF matrix of K PS M-PAM constellation
- $\mathbf{W} = [\boldsymbol{w}_1 \ \ \boldsymbol{w}_2 \cdots \ \boldsymbol{w}_K]$: precoding matrix

➡ Non-convex problem with multiple variables

Initial results

❑ Scenario and system parameters

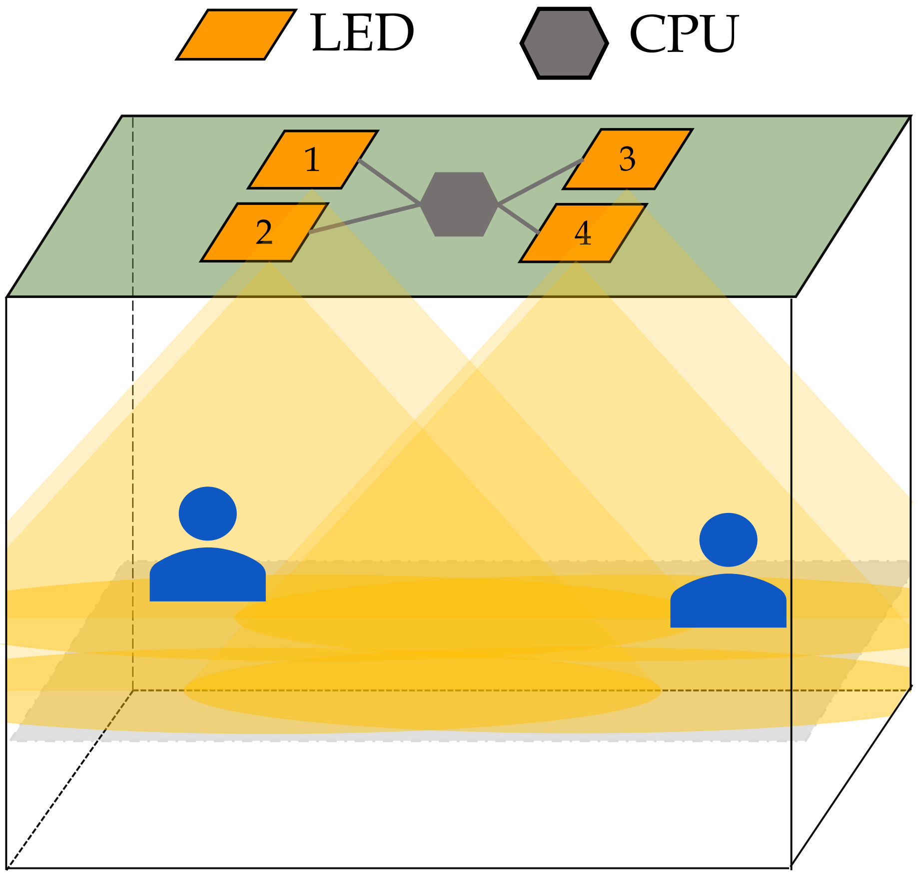
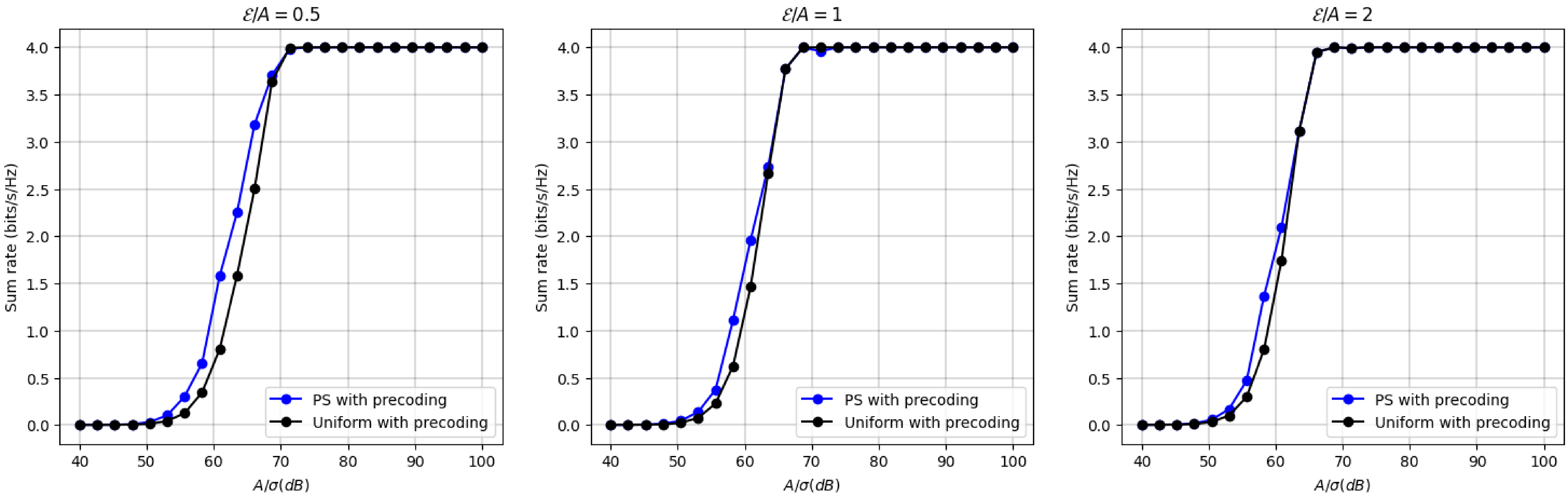


Table 1: System Parameters

Room and LED configurations	
Room dimension (Length × Width × Height)	5 (m) × 5 (m) × 3 (m)
LED positions	luminary 1 : $\left(-\sqrt{2},-\sqrt{2},3\right)$, luminary 2 : $\left(\sqrt{2},-\sqrt{2},3\right)$ luminary 3 : $\left(\sqrt{2},\sqrt{2},3\right)$, luminary 4 : $\left(-\sqrt{2},\sqrt{2},3\right)$
LED bandwidth, B	20 MHz
LED beam angle, ϕ	120° (LED Lambertian order is 1)
LED conversion factor, η	0.44 W/A
Receiver photodetectors	
Active area, A_r	1 cm^2
Responsivity, γ	0.54 A/W
Field of view (FOV), Ψ	60°
Optical filter gain, $T_s(\psi)$	1
Refractive index of the concentrator, κ	1.5
Noise variance, σ^2	1
Other parameters	
Ambient light photocurrent, χ_{amp}	10.93 $A/(m^2 \cdot Sr)$
Preamplifier noise current density, i_{amp}	5 $pA/Hz^{-1/2}$

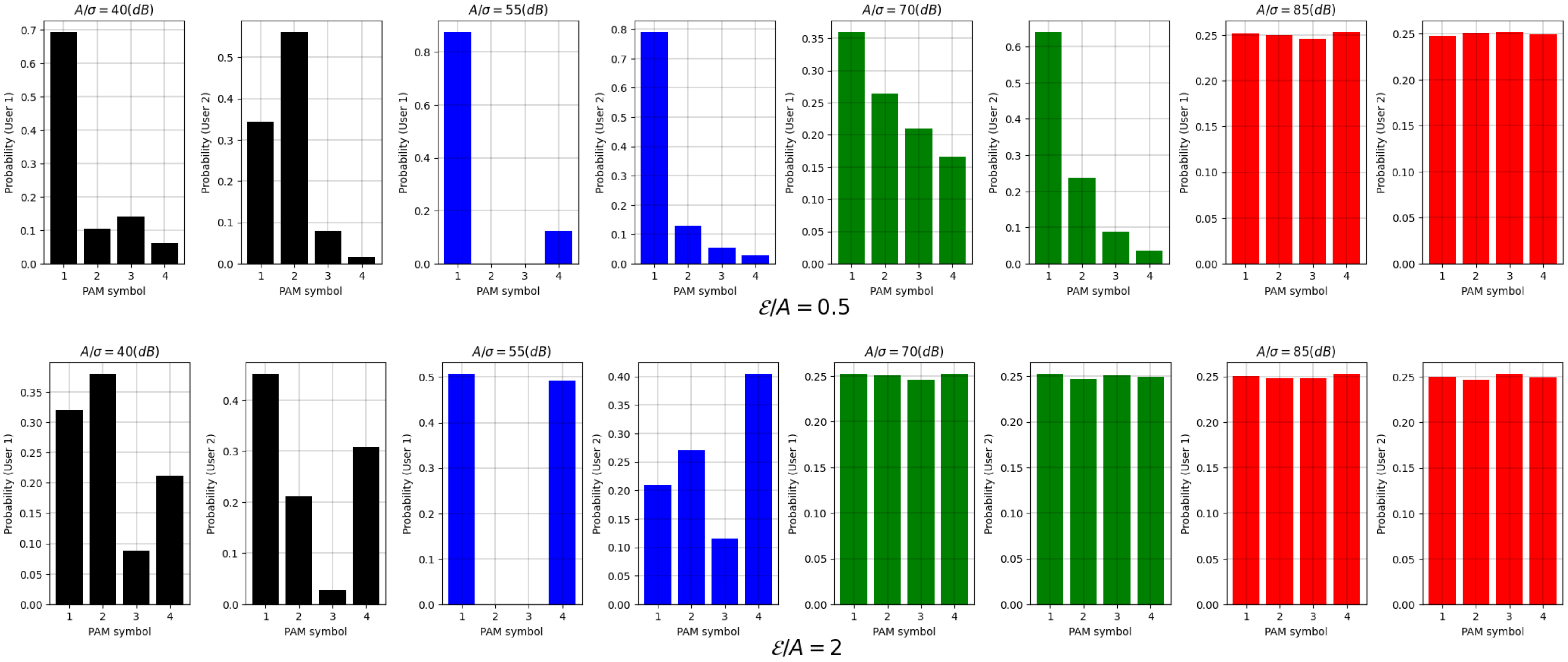
Initial results

- Sum rate optimization



Initial results

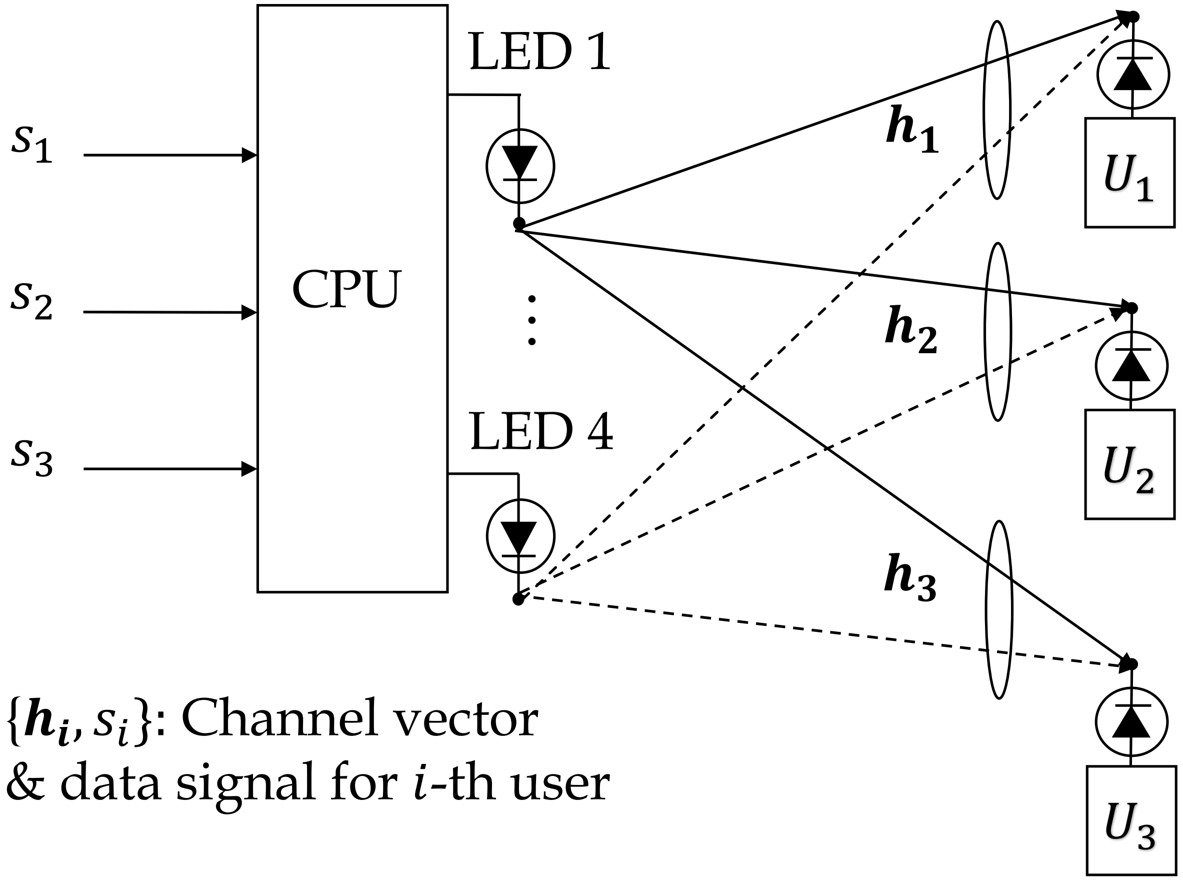
- Optimal PMF of PS 4-PAM



Thank you for listening!

Q & A

Receiver signal at i-th user: y_i



$$y_1 = f(\boldsymbol{h_1}, s_1, s_2, s_3)$$

$$y_2 = f(\boldsymbol{h_2}, s_2, s_1, s_3)$$

$$y_3 = f(\boldsymbol{h_3}, s_3, s_1, s_2)$$

MUI

How to reduce MUI ?