Research Progress Seminar

Joint Design of Probabilistic Constellation Shaping and Precoding for Multi-user VLC Systems

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Contents

Introduction

❑ Visible light communication (VLC)

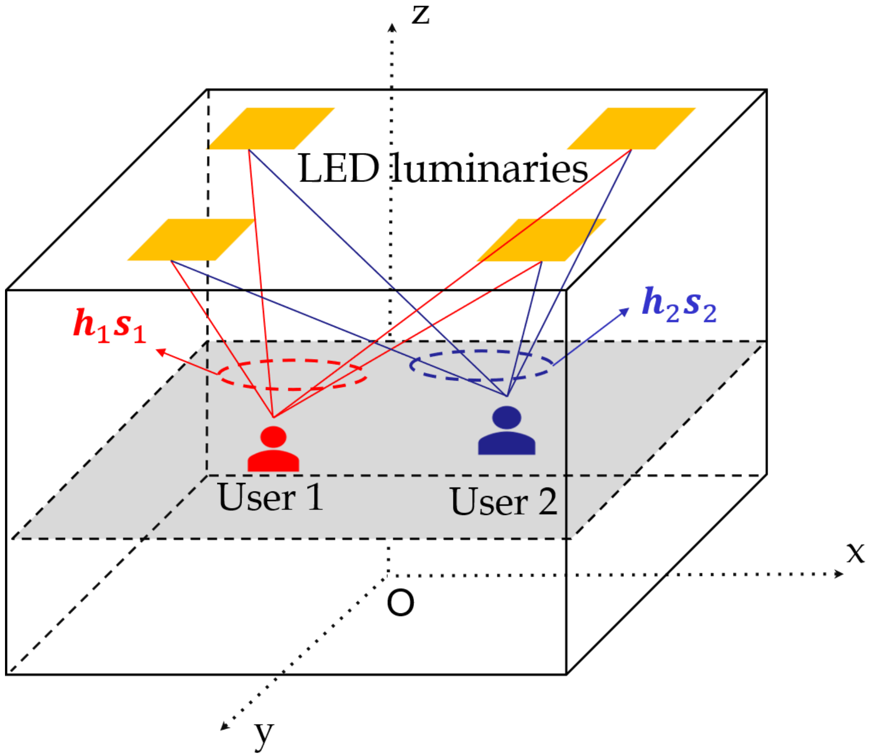
- ❖ Dual functionality
  - Illumination (primary)
  - Communication (secondary)
- ❖ Immunity to interference from other electromagnetic sources
- ❖ Environment friendly
  - Hospital
  - Airplane

VLC network is expected to support multiple mobile users.

Introduction

❑ Multi-user VLC system (MU-VLC)

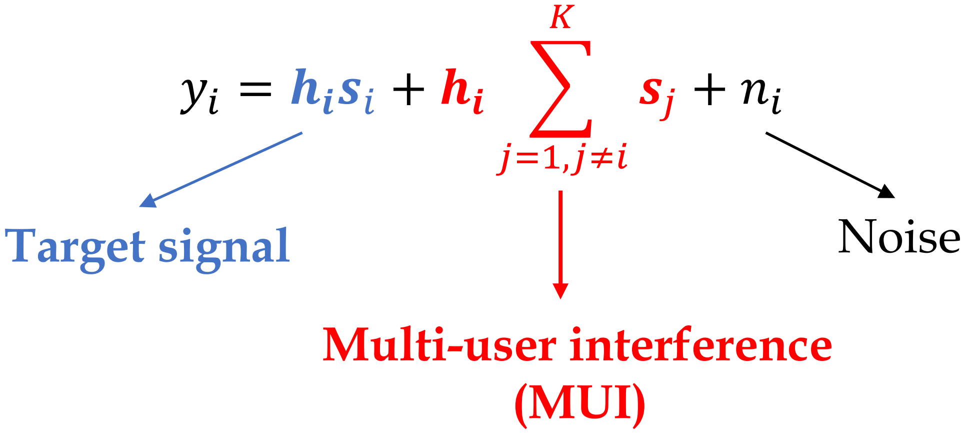
- Multiple LED luminaries
- Multiple users



$\boldsymbol{h}_i$: Channel vector of user i-th

$\boldsymbol{s}_i$: Uniform data symbol vector for user i-th

❖ The received signal at i-th user:



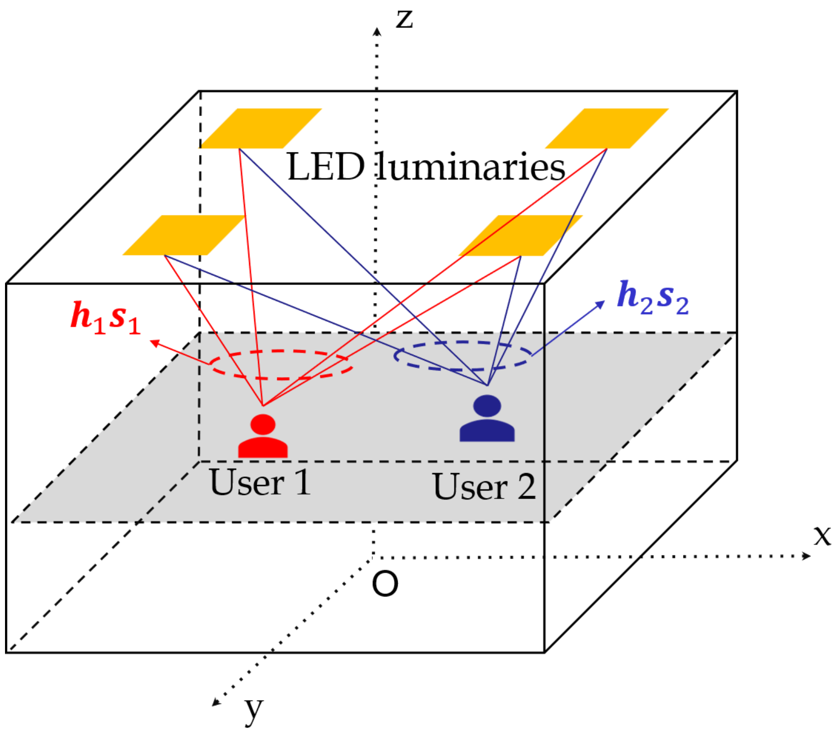
$$y_i = \underbrace{\boldsymbol{h}_i \boldsymbol{s}_i}_{\text{Target signal}} + \underbrace{\boldsymbol{h}_i \sum_{j=1, j \neq i}^{K} \boldsymbol{s}_j}_{\text{Multi-user interference (MUI)}} + \underbrace{n_i}_{\text{Noise}}$$

❖ The existence of MUI is based on the observation that the transmit signals for different users are superimposed in multi-user transmissions

❖ MUI is the most challenging issue in the MU-VLC systems

Introduction

❑ Multi-user VLC system (MU-VLC)



- ❖ The received signal at *i*-th user:

$$y_i = \boldsymbol{h}_i \boldsymbol{s}_i + \boldsymbol{h}_i \sum_{j=1,j\neq i}^{K} \boldsymbol{s}_j + n_i$$

Target signal

Multi-user interference (MUI)

Noise

- ❖ The average received SNR at *i*-th user:

$$\gamma_i = \frac{|\boldsymbol{h}_i \boldsymbol{w}_i|^2}{|\boldsymbol{h}_i \sum_{j=1,j\neq i}^{K} \boldsymbol{w}_j|^2 + \sigma_i^2}$$

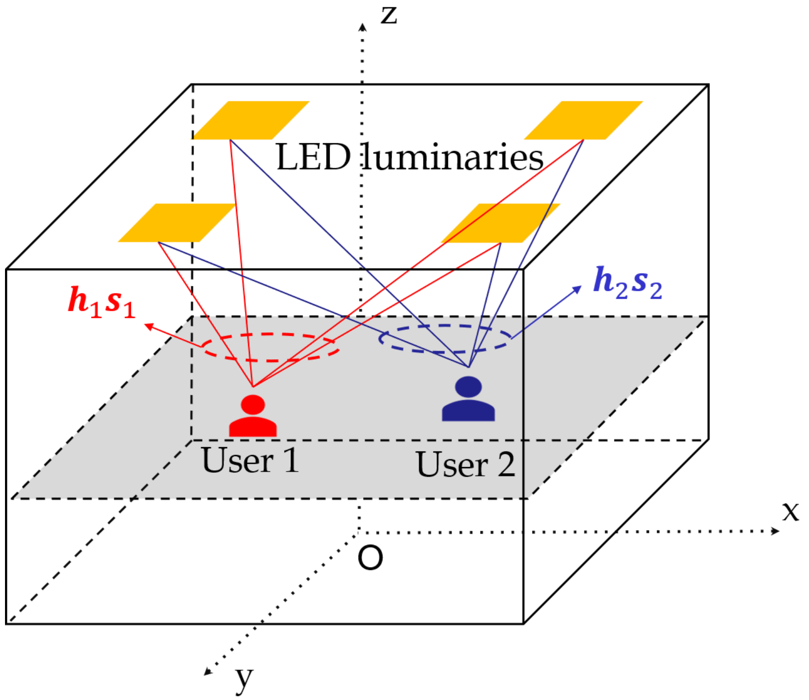
➡ MUI is the performance-limiting factor that degrades the received signal quality

Decrease users' achievable rate

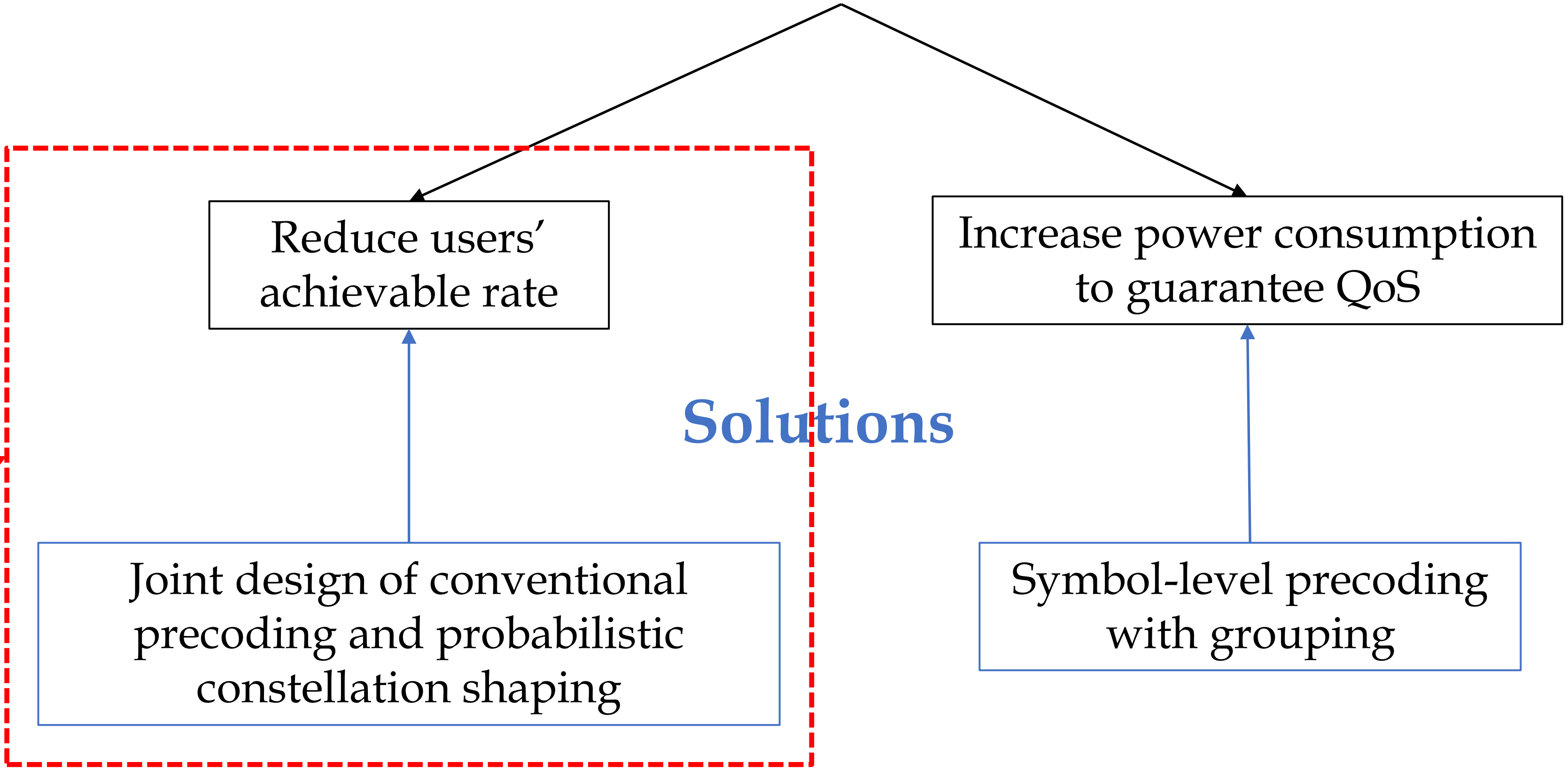
Increase power consumption to guarantee QoS

Introduction

- Original contributions



- MUI is the performance-limiting factor that degrades the received signal quality



Reduce users' achievable rate

Increase power consumption to guarantee QoS

Solutions

Joint design of conventional precoding and probabilistic constellation shaping

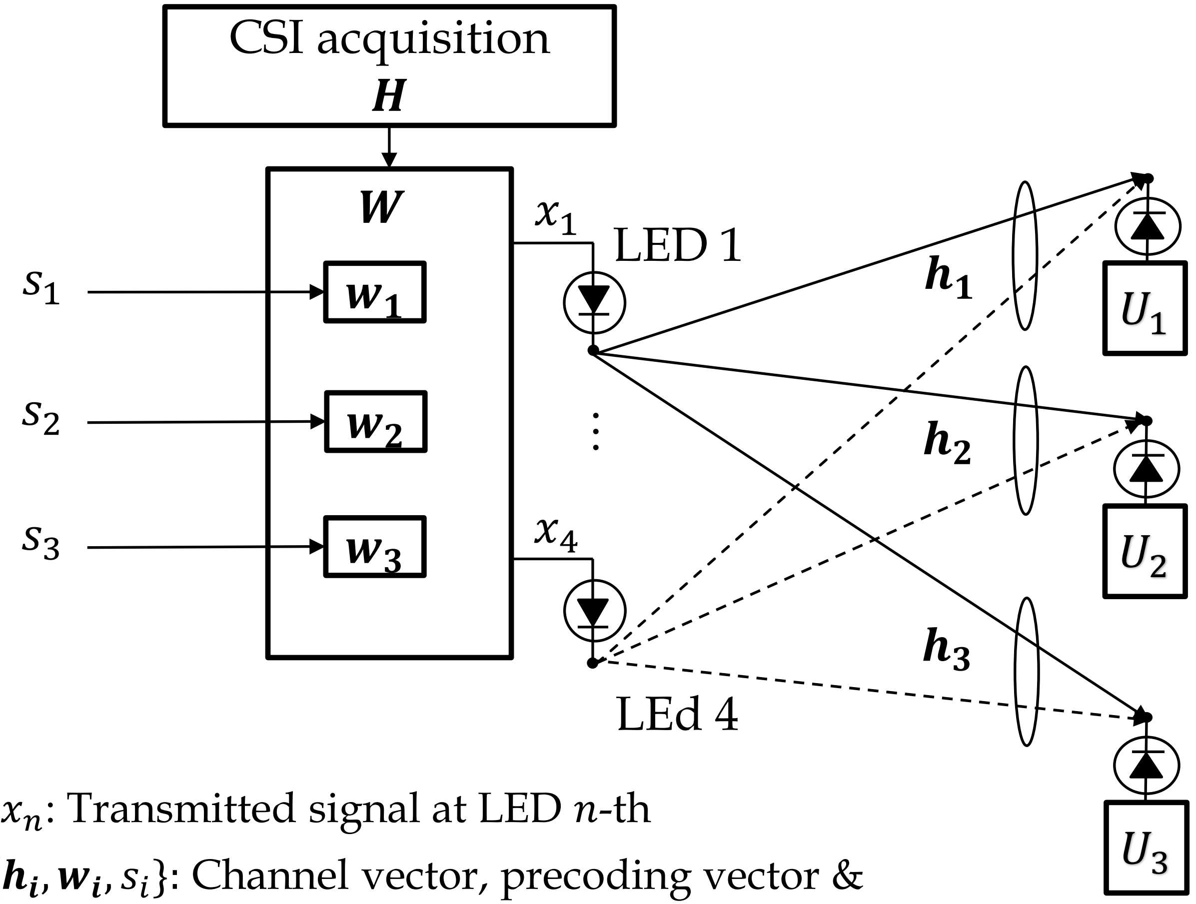
Symbol-level precoding with grouping

Seminar's topic

Introduction

☐ Conventional precoding

- Linearly encoding s_i by a vector $\boldsymbol{w_i}$ to reduce the effect of **multi-user interference (MUI)** in the multi-user transmission



x_n: Transmitted signal at LED n-th

$\{\boldsymbol{h_i}, \boldsymbol{w_i}, s_i\}$: Channel vector, precoding vector & **uniform** data symbol for i-th user

☐ Received signal at the i-th user

$$y_i = \underbrace{\boldsymbol{h_i w_i} s_i}_{\textbf{Target signal}} + \underbrace{\boldsymbol{h_i} \sum_{j=1, j\neq i}^{K} \boldsymbol{w_j} s_j}_{\textbf{MUI}} + \underbrace{n_i}_{\text{Noise}}$$

Problem: With a large number of users K

→ A noisy channel with MUI

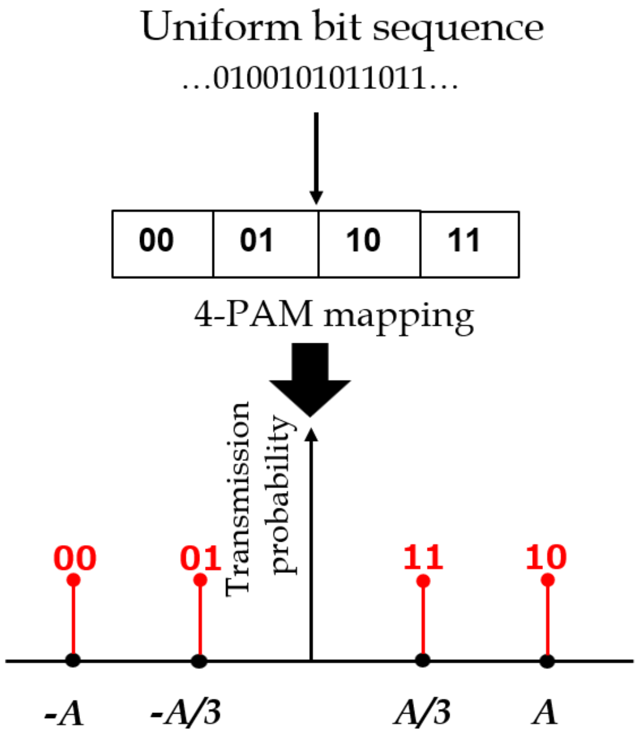
Precoding is not effective

Uniform data symbols are susceptible to noise

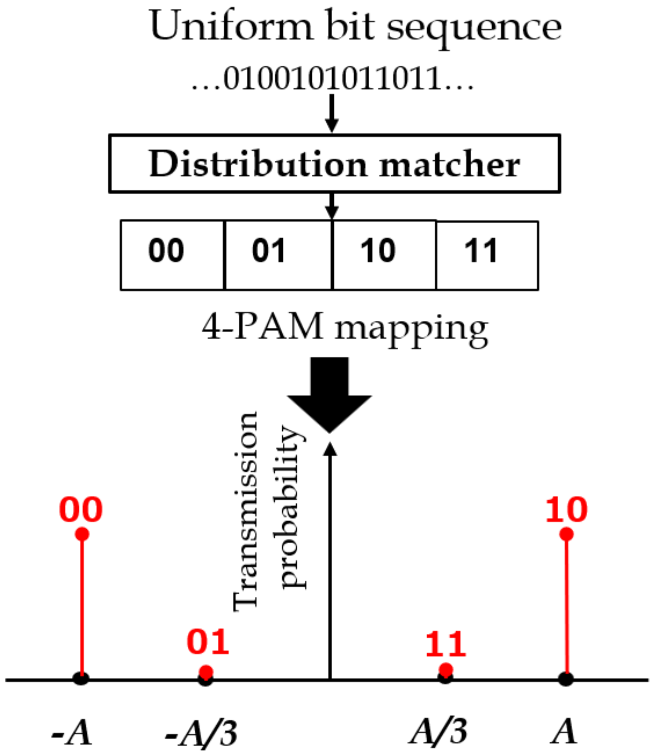
Reduce users' achievable rates

Introduction

❑ Probabilistic constellation shaping (PCS)



Conventional uniform data symbol



Probabilistically shaped symbol

- PCS is an approach to improve the achievable rate by **designing the symbol transmission probability**
- PCS can be deployed along with precoding design to exploit both the diversity and shaping gain to improve the users' achievable rates

Introduction

Precoding technique

Probabilistic constellation shaping

Goal: An optimal joint design solution for precoding and probabilistic constellation shaping for the multi-user VLC system

- Reduce multi-user interference effect
- Improve the sum-rate performance

Challenges:

- Fairly complex (both theoretical and practical) problem with multiple variables
- Fast algorithm that is suitable for a practical, dynamic environment
- Most recent (in 2022) studies solve the problem with single-user cases [1,2]

Current Solution:

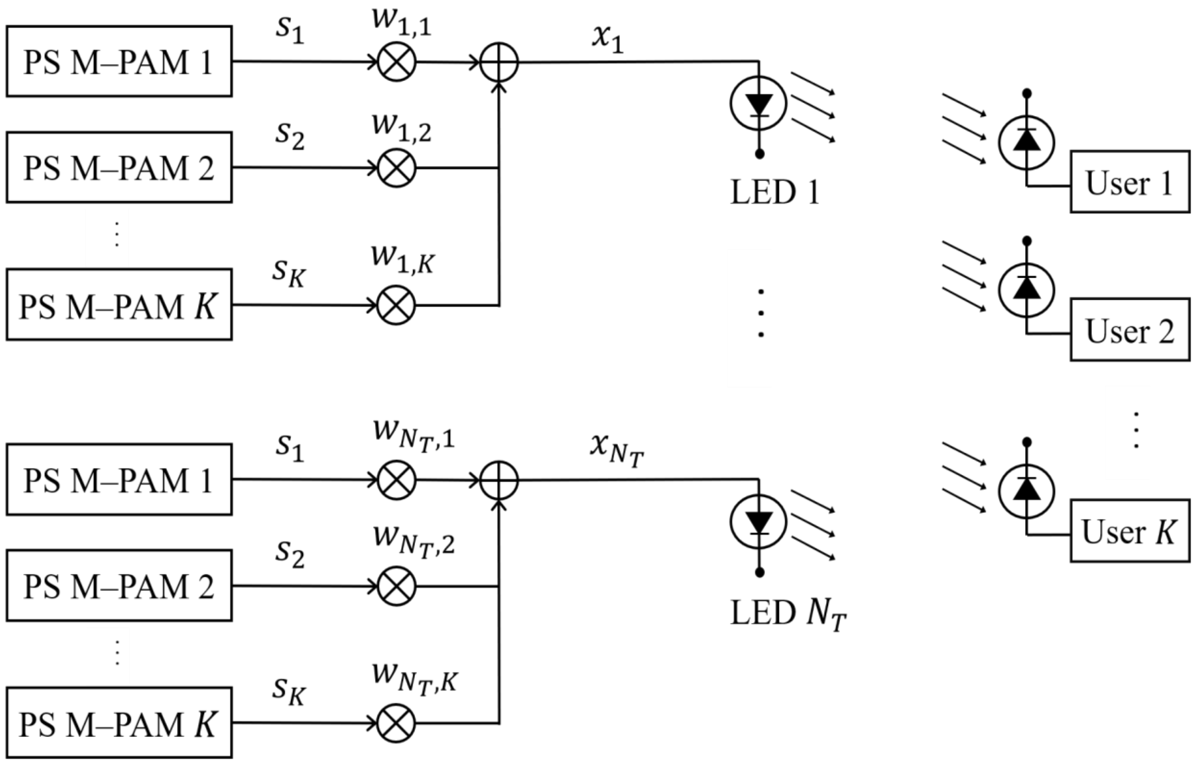
- **Propose a near-global optimal solution** based on a metaheuristic algorithm. The algorithm is still computationally complex: gives the theoretical limits but is not applicable to practical design
- **Propose a local optimal solution** with low complexity that is suitable for practical deployment

[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.

[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.

System model

- MU-MISO VLC system with precoding and 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.

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

- $\boldsymbol{w}_k = [w_{k,1} \quad w_{k,2} \cdots \quad w_{k,N_T}]$ is the precoding vector for user k.
- x_n: Transmitted signal at LED n-th

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

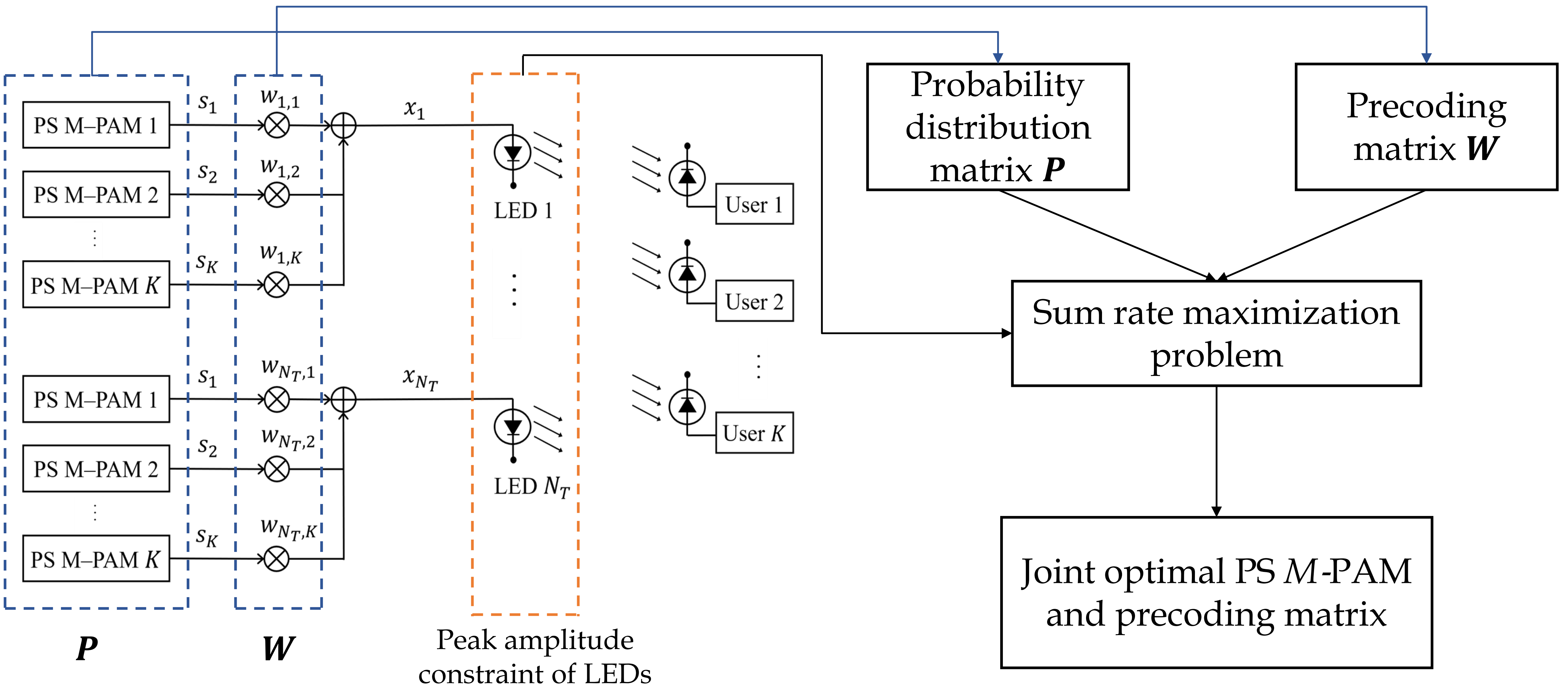
Amplitude vector: $\boldsymbol{a_k} = [a_{k,1} \quad a_{k,2} \cdots \quad a_{k,M}]$

→ Fixed value based on LED’s peak amplitude.

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.

Problem formulation



Probability distribution matrix $\boldsymbol{P}$

Precoding matrix $\boldsymbol{W}$

Sum rate maximization problem

Joint optimal PS M-PAM and precoding matrix

Problem formulation

❑ Problem formulation

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

→ Sum rate maximization

$$\text{subject to}$$

$$\left\| [\mathbf{W}]_{n,:} \right\|_1 \leq 1,$$

→ Peak amplitude constraint

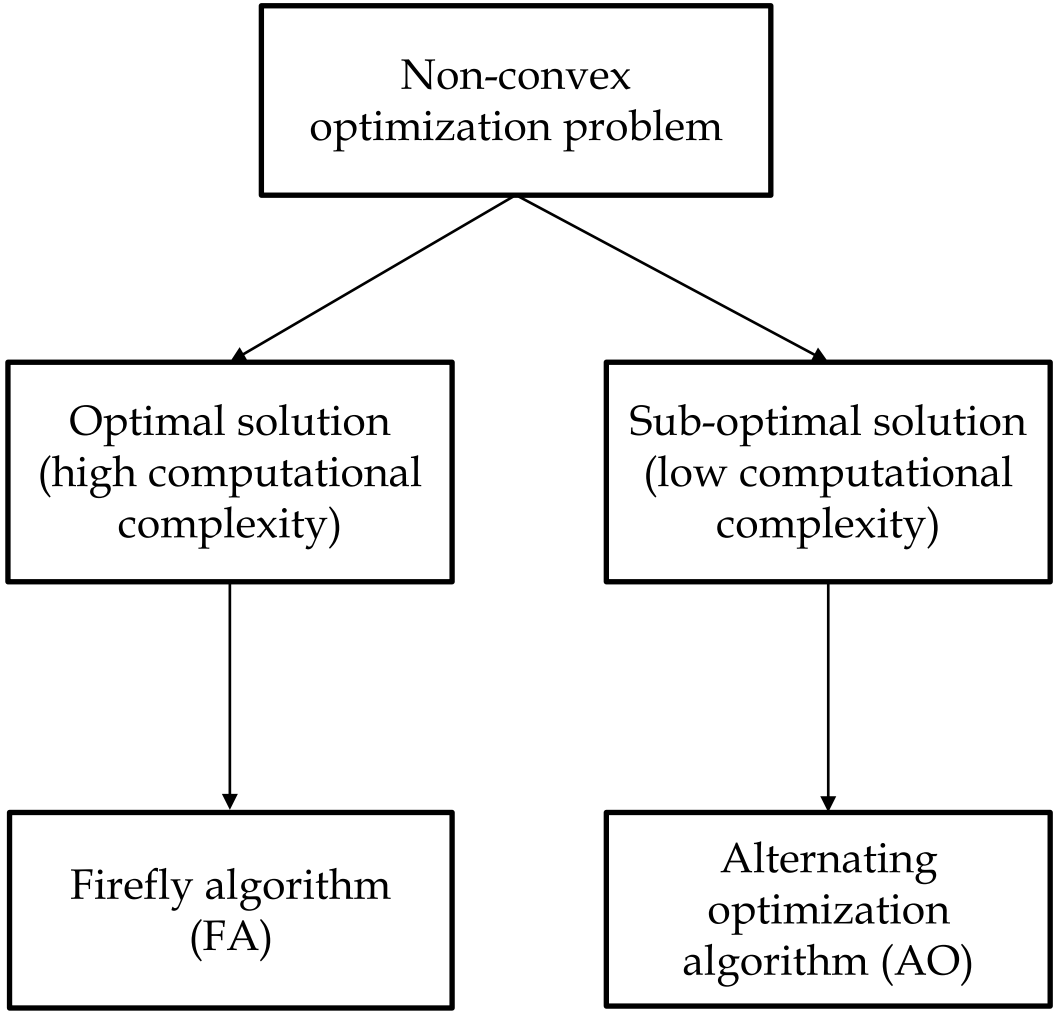
$$\left. \begin{aligned} 0 \leq \mathbf{P} \leq 1, \\ \mathbf{P} \times \mathbf{1}_M = \mathbf{1}_K, \end{aligned} \right\}$$

→ Constraint for symbol distribution matrix

❑ Optimization variables

- $\mathbf{P} = [\boldsymbol{p}_1 \ \ \boldsymbol{p}_2 \cdots \ \boldsymbol{p}_K]$: 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



Non-convex optimization problem

Optimal solution (high computational complexity)

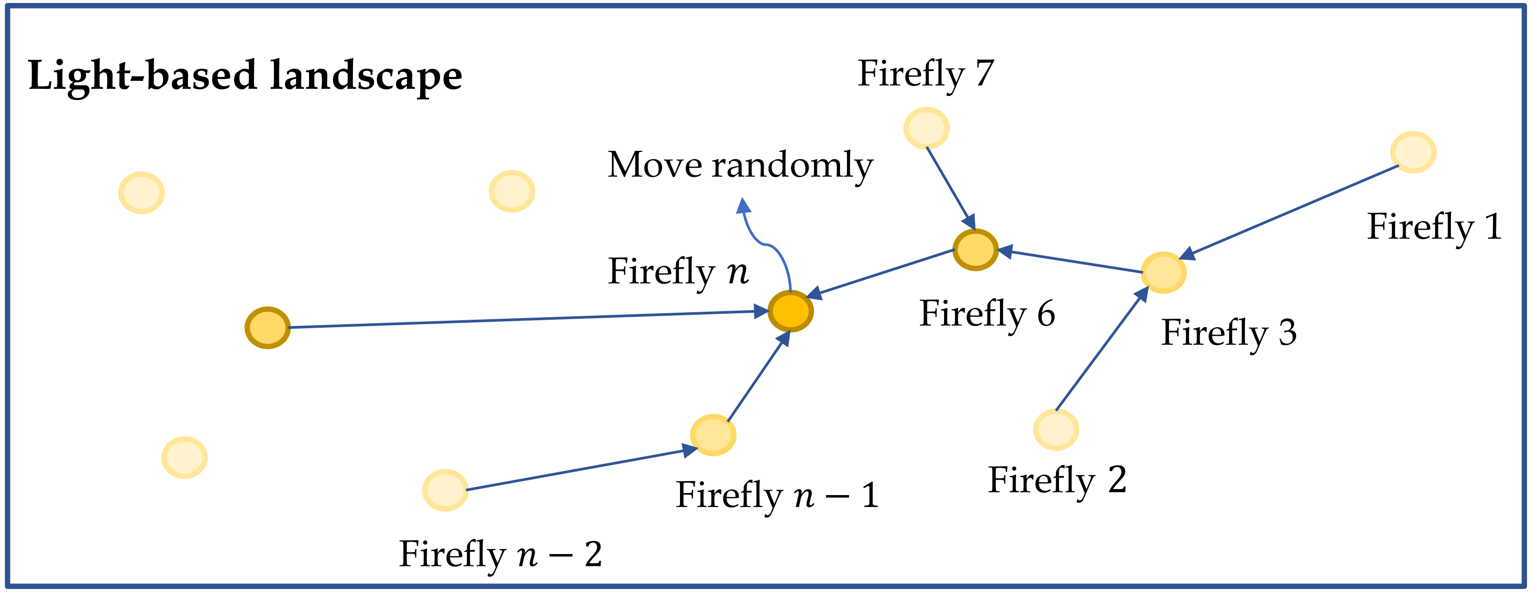
Sub-optimal solution (low computational complexity)

Firefly algorithm (FA)

Alternating optimization algorithm (AO)

Solution-FA

- ☐ The firefly algorithm (FA) was developed by Prof. Xin-She Yang in 2008
- ☐ It is a Nature-Inspired Optimization Algorithms (metaheuristic algorithm)



- The objective landscape maps to a light-based landscape
- Each firefly represents a solution, the brightness of a firefly is a value of the objective function
- Fireflies swarm into the brighter points/regions, the brightest firefly moves randomly to explore the new region
- After sufficient time, all fireflies swarm into the brightest points/regions.

➡ It tends to be a global optimizer but can be potentially more computationally expensive

Solution-AO

❑ Low complexity solution by applying Zero-forcing (ZF) precoding (**removing all MUI**)

$$
\begin{aligned}
\mathbb{P}\mathbf{3}: \underset{\mathbf{P},\mathbf{W}}{\text{maximize}} \quad & \sum_{k=1}^{K} R_k(\mathbf{P},\mathbf{W}) && \longrightarrow \text{Sum rate maximization} \\
\text{subject to} \quad & \mathbf{h}_k^T \mathbf{w}_i = 0, \ \ \forall i \neq k, && \longrightarrow \text{ZF constraint} \\
& \|[\mathbf{W}]_{n,:}\|_1 \ \leq \ 1, && \longrightarrow \text{Peak amplitude constraint} \\
& \left.\begin{aligned} & \mathbf{0}_{K\times M} \ < \mathbf{P} < \ \mathbb{1}_{K\times M}, \\ & \mathbf{P} \times \mathbb{1}_{M\times 1} = \mathbb{1}_{K\times 1}, \end{aligned}\right\} && \longrightarrow \text{Constraint for symbol distribution matrix}
\end{aligned}
$$

Non-convex problem with multiple variables

Solution: Alternating optimization (AO) approach

- An iterative procedure where, in each iteration, one variable is optimized given the other is fixed

→ The original **non-convex problem** with multiple variables is decomposed into **two one-variable convex problems**

- This process is repeated until a convergence criterion is met

Results and discussions

❑ Scenario and system parameters

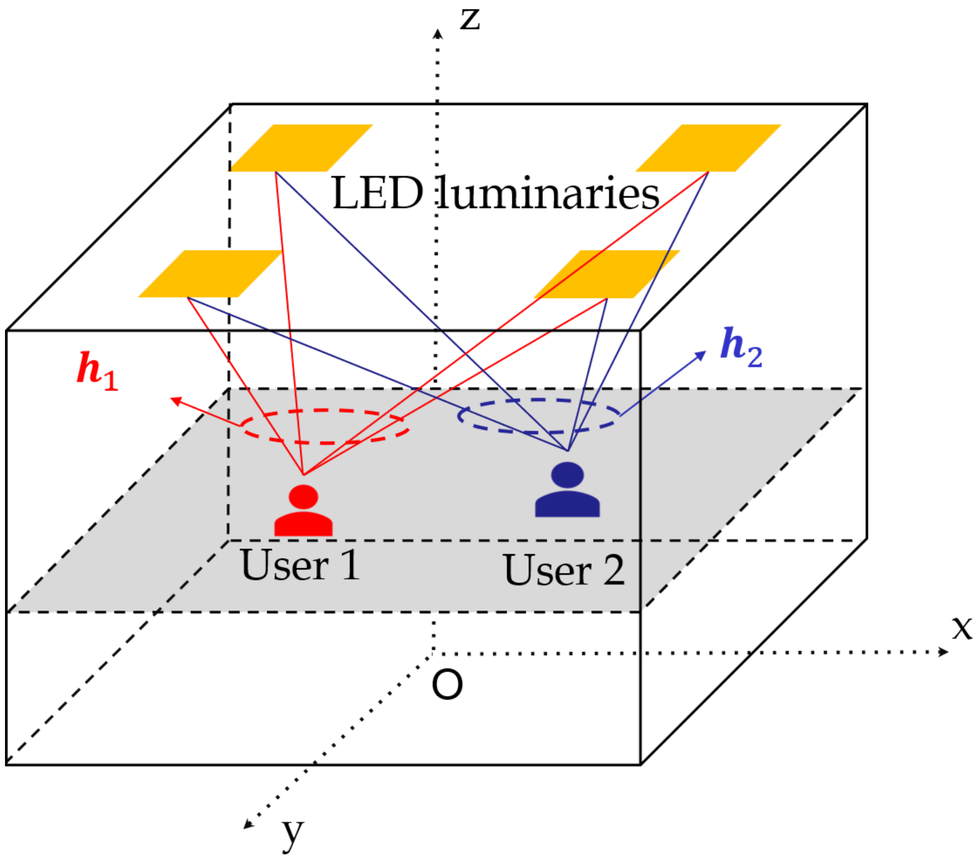
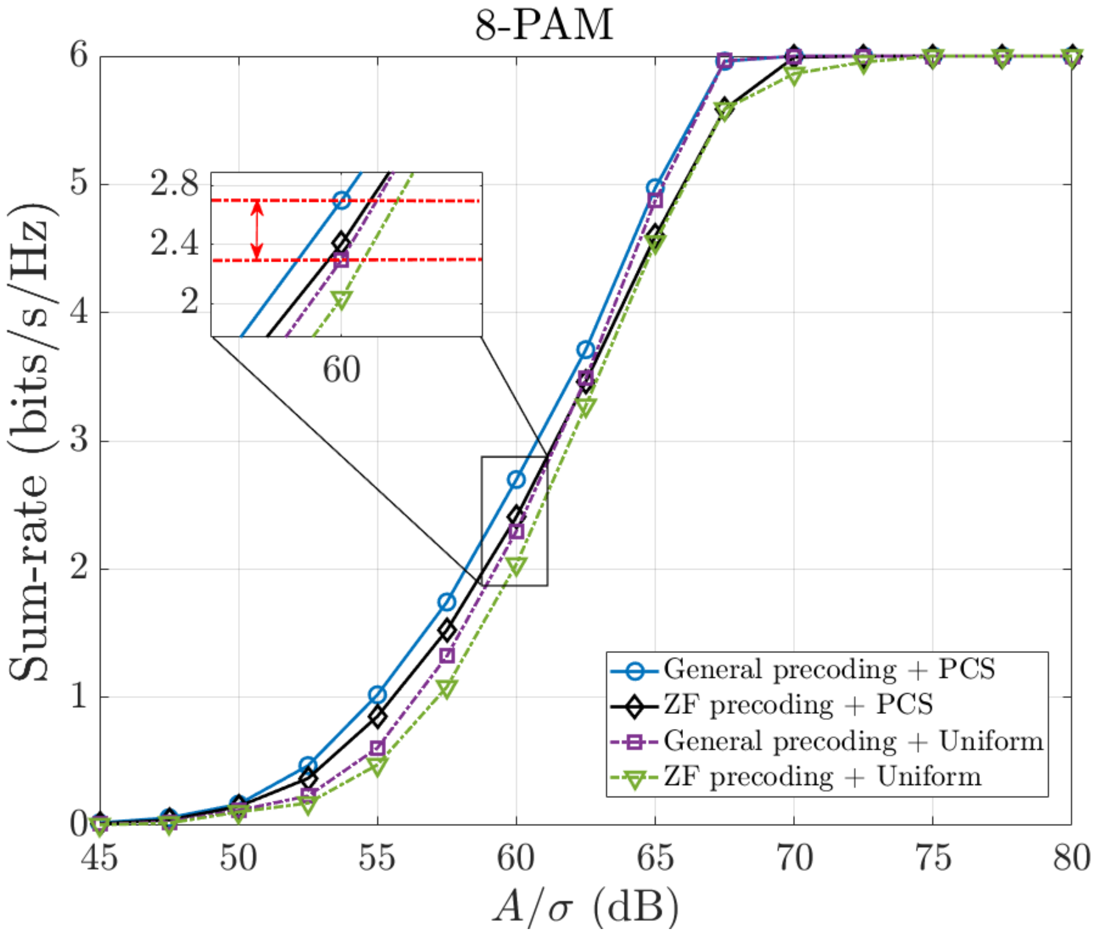


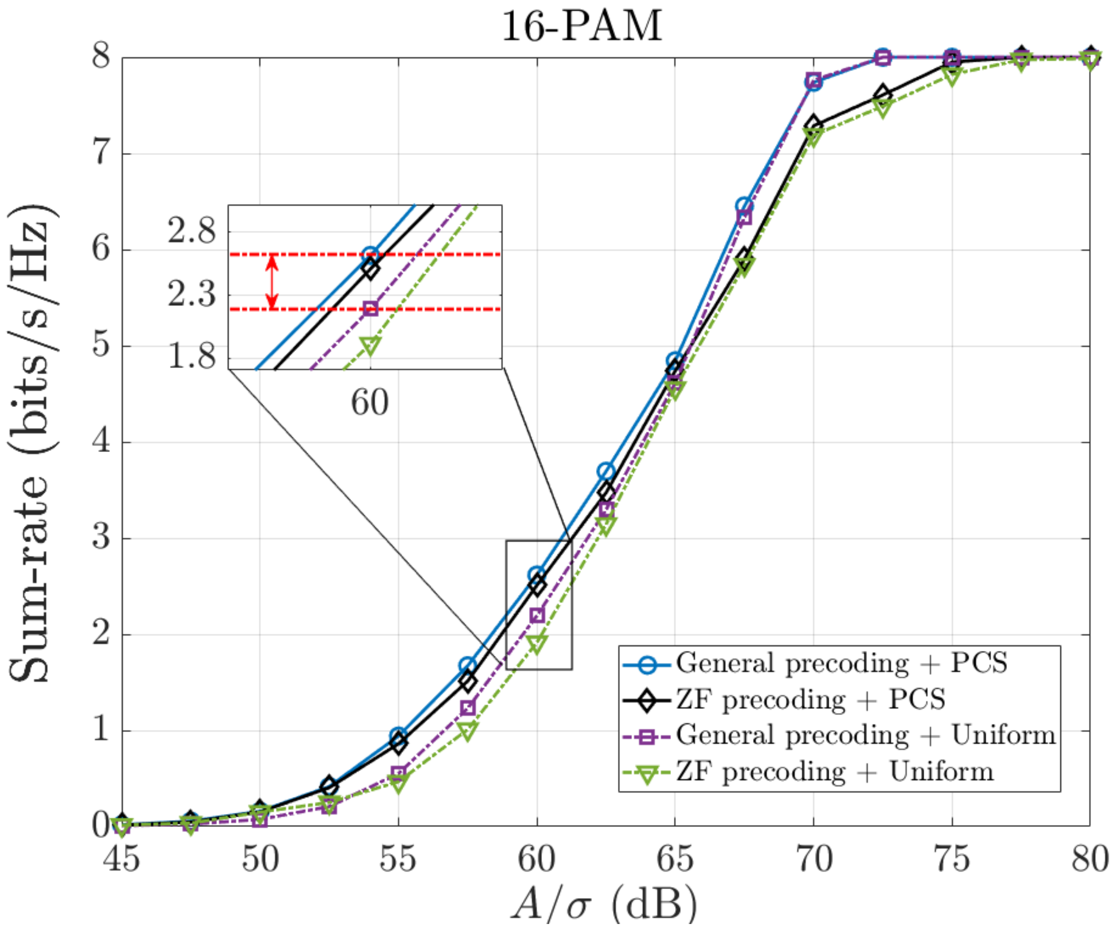
Table 1: System Parameters

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 $\mathrm{A}/(\mathrm{m}^2 \cdot \mathrm{Sr})$
Preamplifier noise current density, i_{amp}	5 $\mathrm{pA}/\mathrm{Hz}^{-1/2}$

Results and discussions

- ☐ Sum rate versus the ratio of maximum signal amplitude (A) and noise variation (σ)

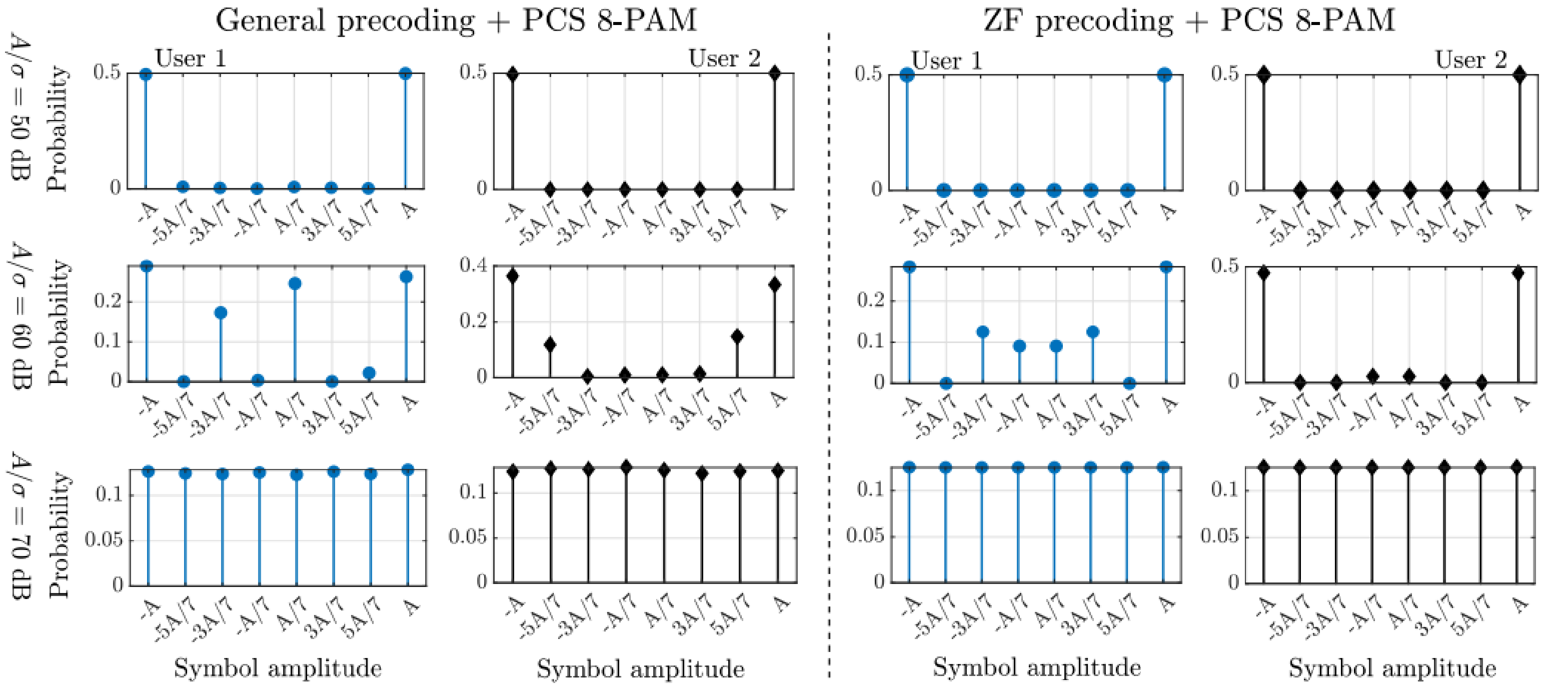




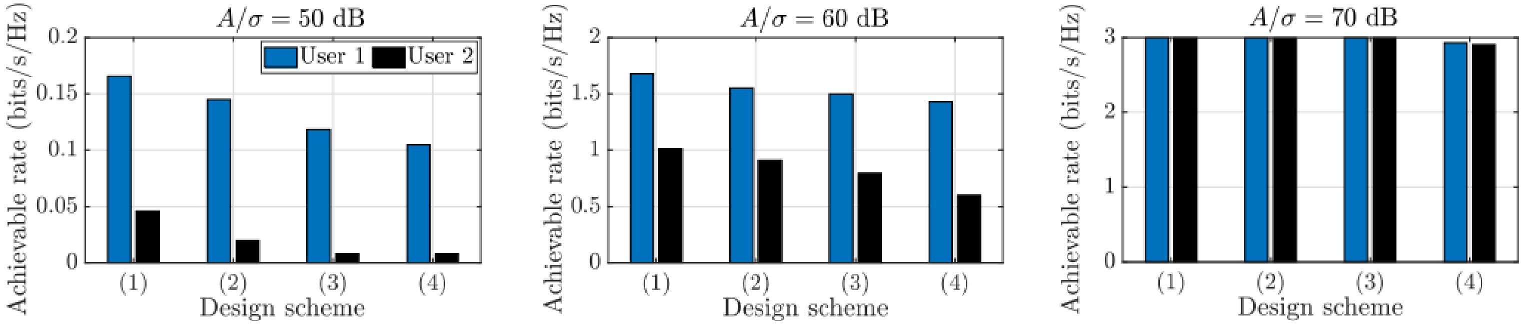
➡ The joint design achieves **17.5%** and **19.2%** higher sum-rate for 8-PAM and 16-PAM

Results and discussions

❑ Optimal users' symbol distribution



(a) Optimal symbol distributions of PCS 8-PAM with different schemes and A/σ values.



(b) User's achievable rate with different A/σ values and schemes:
(1): General precoding + PCS 8-PAM, (2): ZF precoding + PCS 8-PAM
(3): General precoding + Uniform 8-PAM, (4): ZF precoding + Uniform 8-PAM.

Thank you for listening!

Q & A