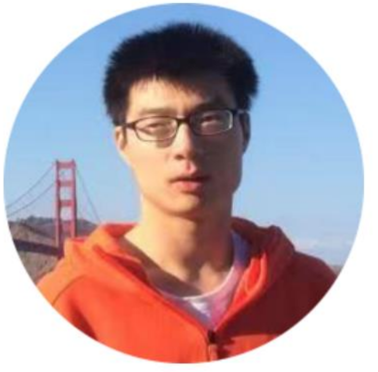
# Signal Shaping Optimization for Nonlinear VLC Systems



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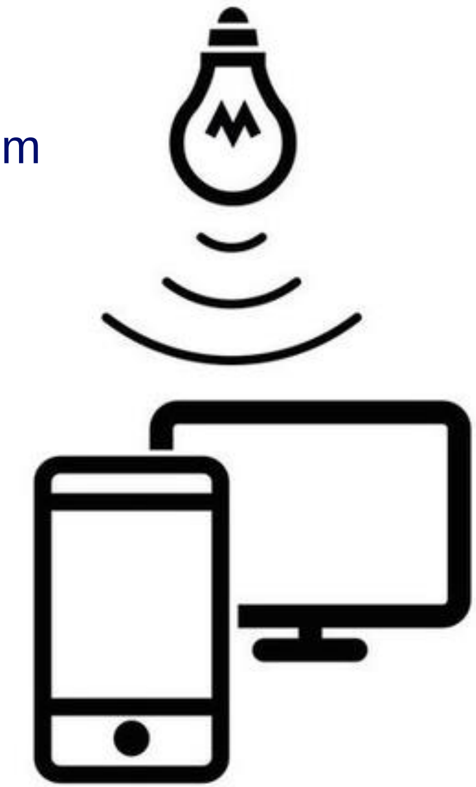
# Outline

# Introduction

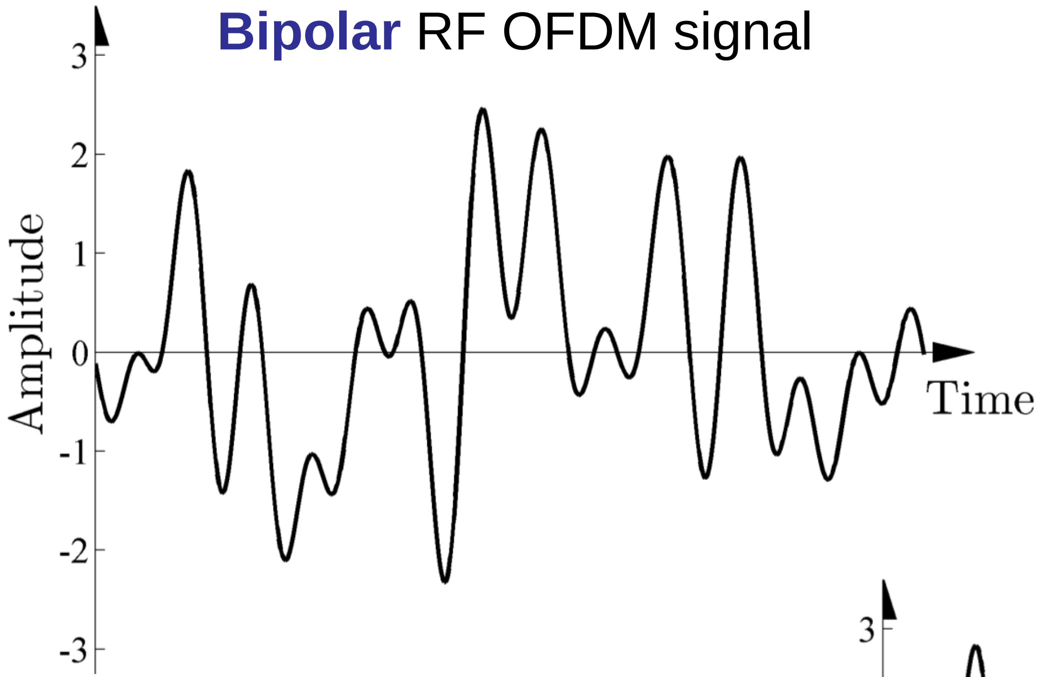
- Benefits of visible light communication (VLC)
  - Vast spectrum resources ⇒ OFDM for broadband system
  - Simple implementation ⇒ DCO-OFDM
  - High spatial reuse
  - Enhanced security
  - Illumination-communication dual functions



- VLC signals and features
  - Intensity modulation and direct detection (IM/DD)
  - Real and nonnegative intensity signals
    - ⇒ require a **unipolar** VLC OFDM signal

# From Bipolar to Unipolar

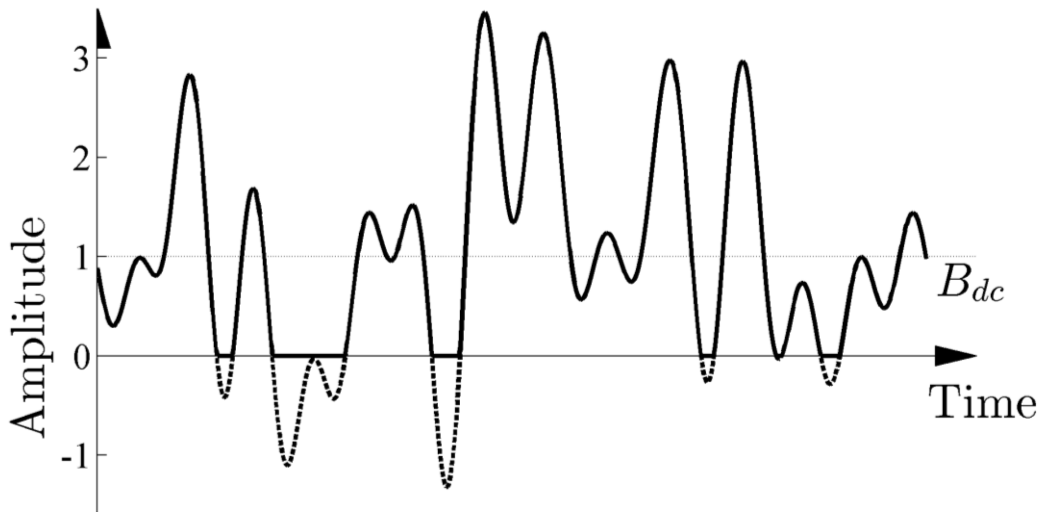
**Bipolar** RF OFDM signal




**1. Biasing**

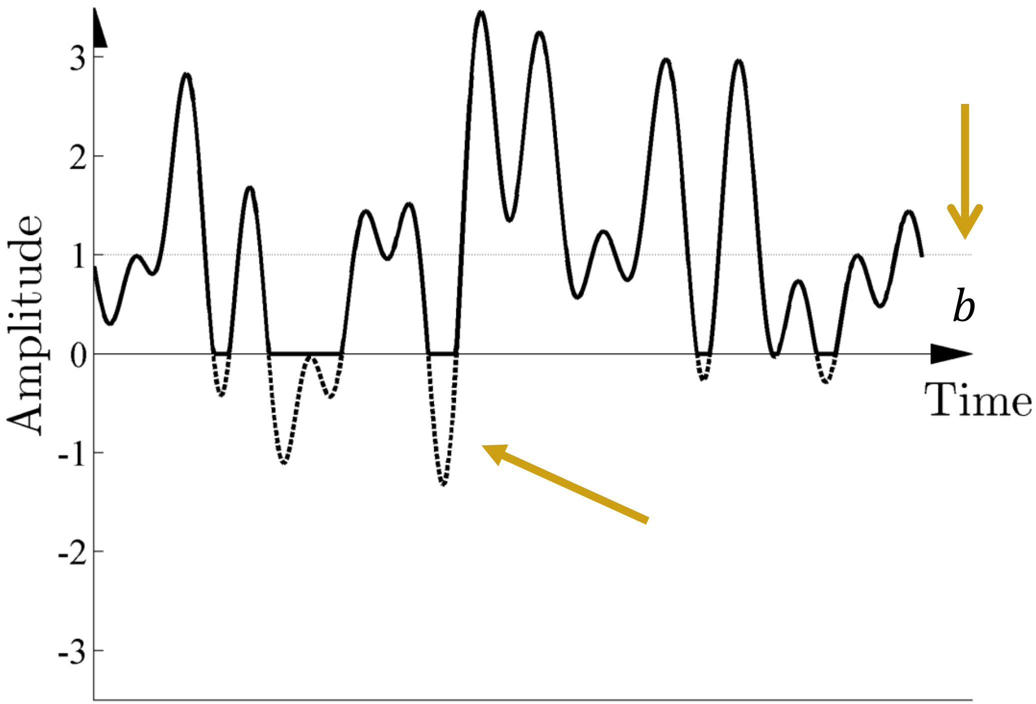
**2. Clipping**

**Unipolar** VLC OFDM signal



# Bias-Power Trade-off

**Unipolar** VLC OFDM signal




- Direct-Current Bias (**DC-Bias**) $b$

**TRADE-OFF**

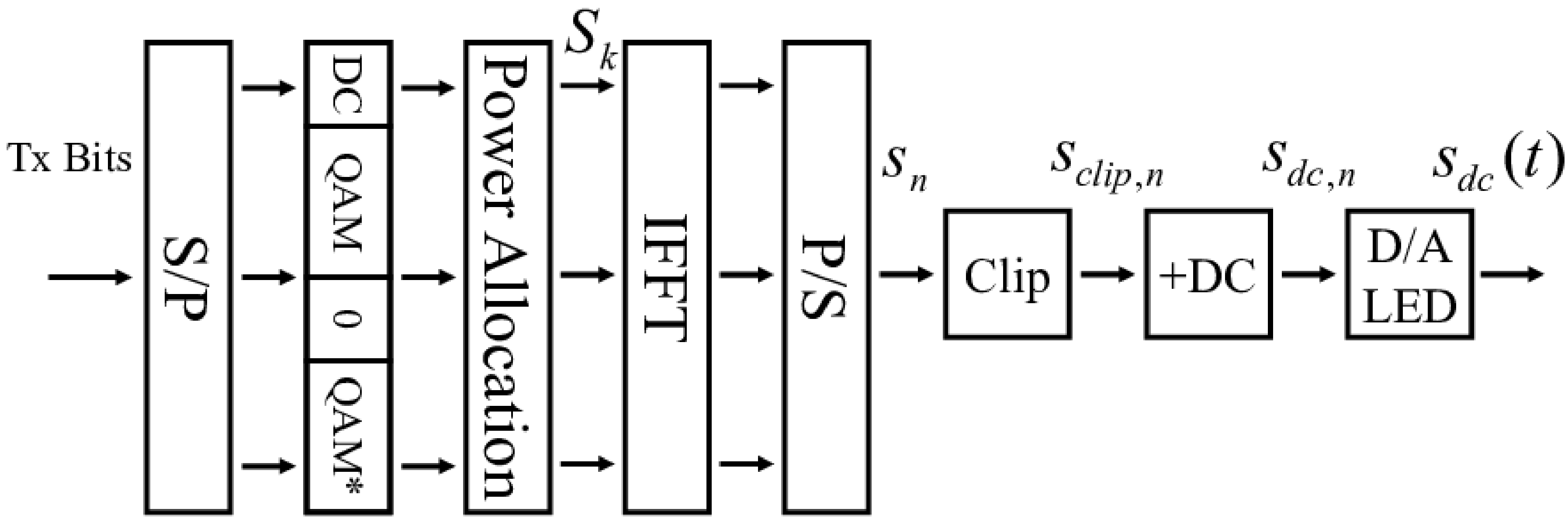
- Information-Carrying Power (**IC-Power**) $\sigma^2 = \mathrm{Var}[s(t)]$

- **High** DC bias causes **a waste of power.**
- **Low** DC bias causes **a severe clipping distortion.**
- Trade-off between **power consumption** and **clipping distortion.**

# Outline

# System Model

- **DCO-OFDM transmitter model**



# System Model

- **DCO-OFDM transmitter model**

- **Optical channels**

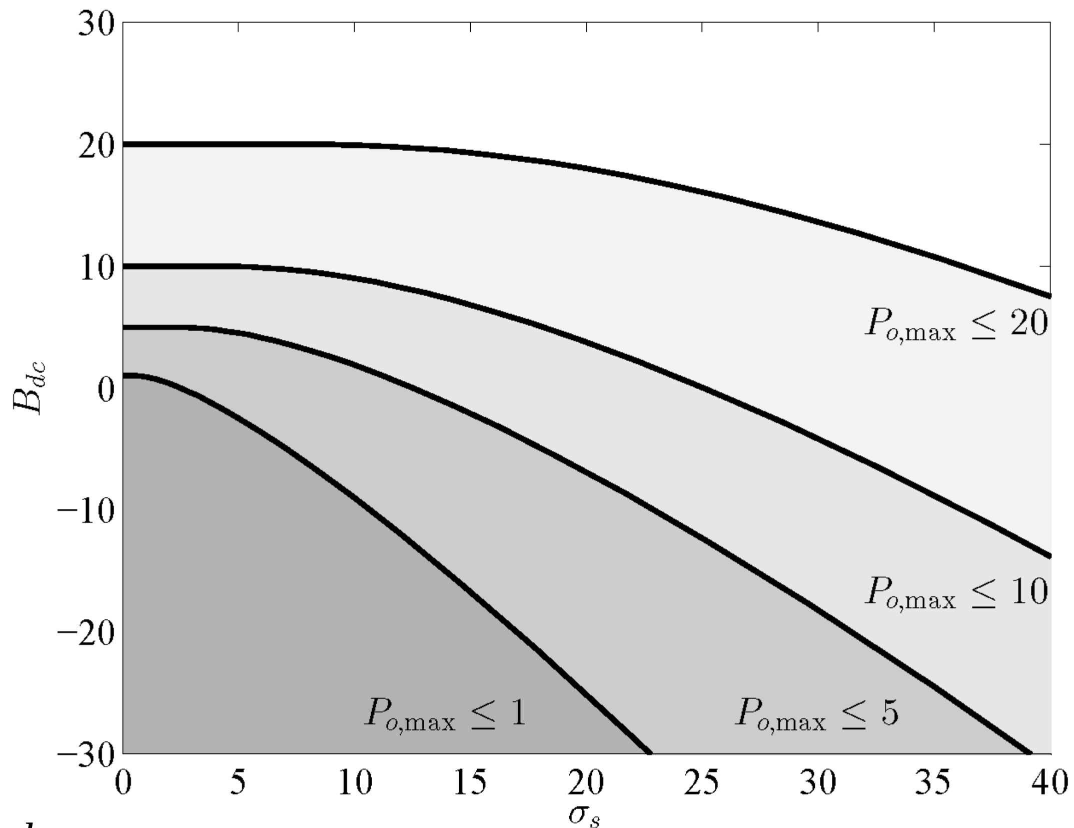
  $$Y_k = H_k S_{dc,k} + N_k$$

  - **Flat channels**
  - Dispersive channels

- **Optical power constraint**

  $$P_o(b,\sigma_s) = \mathbb{E}[s_{dc}(t)] \le P_{o,\max}$$

- Where
- $P_o(b,\sigma_s) = \sigma_s \phi(b/\sigma_s) + bQ(b/\sigma_s) \neq b$
- Usually, the optical power is not equal to the bias.




- **Clipping process**

  $$s_{clip,n} = \mathrm{clip}[s_n; -b] = \begin{cases} s_n & s_n > -b \\ -b & s_n \le -b. \end{cases}$$

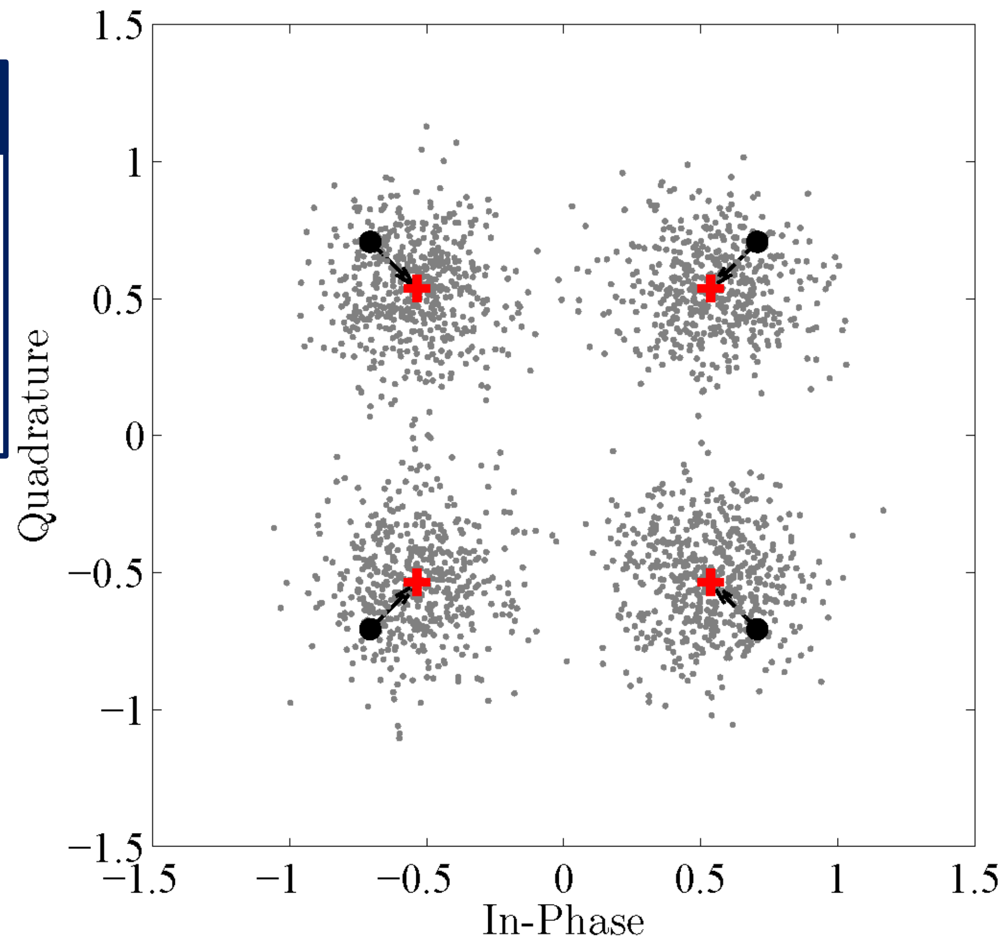
# Clipping Model

**Lemma 1 [Bussgang'1952]**

The clipping process can be modeled in the frequency domain as

$$S_{clip,k} = aS_k + N_{clip,k}.$$

- Attenuation factor
$$a = 1 - Q(b/\sigma_s)$$
- Clipping noise $N_{clip,k} \sim \mathcal{CN}(0, \sigma_{clip}^2)$
- Clipping noise power [Dimitrov'2012]
$$\sigma_{clip}^2 = \sigma_s^2 + (b^2 - \sigma_s^2)Q(b/\sigma_s) - b\sigma_s\phi(b/\sigma_s) - \sigma_s^2 Q(-b/\sigma_s)^2 - \left(\sigma_s\phi(b/\sigma_s) - bQ(b/\sigma_s)\right)^2$$



# Clipping Model

- Impacts of nonlinear clipping process
  - **Shrinkage of the signal power**
  - **Clipping noise**
- The signal-to-noise-and-distortion ratio (**SNDR**) at carrier k:

$$\mathrm{SNDR}_k = \frac{\text{Effective Signal Power}}{\text{Clipping Noise Power} + \text{Background Noise Power}}$$

$$= \frac{\left|H_k\right|^2 a^2 \sigma_s^2}{\left|H_k\right|^2 \sigma_{clip}^2 + \sigma_n^2}$$

where

- Channel gain at carrier k: $H_k$
- Attenuation factor: $a = 1 - Q(b/\sigma_s)$
- Information-carrying power: $\sigma_s^2$
- Background noise power: $\sigma_n^2$
- Clipping noise power: $\sigma_{clip}^2 = \sigma_s^2 + \left(b^2 - \sigma_s^2\right)Q(b/\sigma_s) - b\sigma_s\phi(b/\sigma_s) - \sigma_s^2 Q(-b/\sigma_s)^2 - \left(\sigma_s\phi(b/\sigma_s) - bQ(b/\sigma_s)\right)^2$

# Signal Shaping Optimization

- Under the **optical power** constraint
- Goal: maximize the **achievable rate *R***
- Optimization variables:
  - **DC bias *b***
  - **Information-carrying power $\sigma_s^2$**
- Our problem is

$$\begin{aligned} &\underset{b,\sigma_s^2}{\text{maximize}} \quad R=\sum_{k=1}^{K-1}\log(1+\text{SNDR}_k) \\ &\text{subject to} \quad P_o(b,\sigma_s)\le P_{o,\max} \end{aligned}$$

- Recall that
  - $\text{SNDR}_k = \frac{|H_k|^2 a^2 \sigma_s^2}{|H_k|^2 \sigma_{clip}^2 + \sigma_n^2}$
  - Optical power $P_o(b,\sigma_s) = \sigma_s \phi(b/\sigma_s) + bQ(b/\sigma_s)$

# Signal Shaping Optimization

$$\begin{aligned} &\underset{B_{dc},\sigma_s^2}{\text{maximize}} && R=\sum_{k=1}^{K-1}\log(1+\text{SNDR}_k) \\ &\text{subject to} && P_o(B_{dc},\sigma_s)\le P_{o,\max} \end{aligned}$$

- Define the **optical SNR** $\gamma_o = |H|^2\, P_{o,\max}^2/\sigma_n^2$
- Introduce a negative normalized DC bias $\boldsymbol{x = -b/\sigma_s}$
- Reformulate the problem as an **unconstrained** problem with **only one** variable:

$$\underset{x}{\text{maximize}} \quad \text{SNDR}_o(x)=\frac{Q^2(x)}{q_{clip}(x)+q_o^2(x)\gamma_o^{-1}}$$

where

- $q_o(x) = \phi(x) - xQ(x),$
- $q_{clip}(x) = (1+x^2)Q(x) - (1+x^2)Q^2(x) + 2x\phi(x)Q(x) - x\phi(x) - \phi^2(x).$

# Signal Shaping Optimization

$$\underset{x}{\text{maximize}} \quad \text{SNDR}_o(x) = \frac{Q^2(x)}{p_{clip}(x) + p_o^2(x)\gamma_o^{-1}}$$

**Theorem 1 (Optimal Bias) [Ling'TSP2016]**

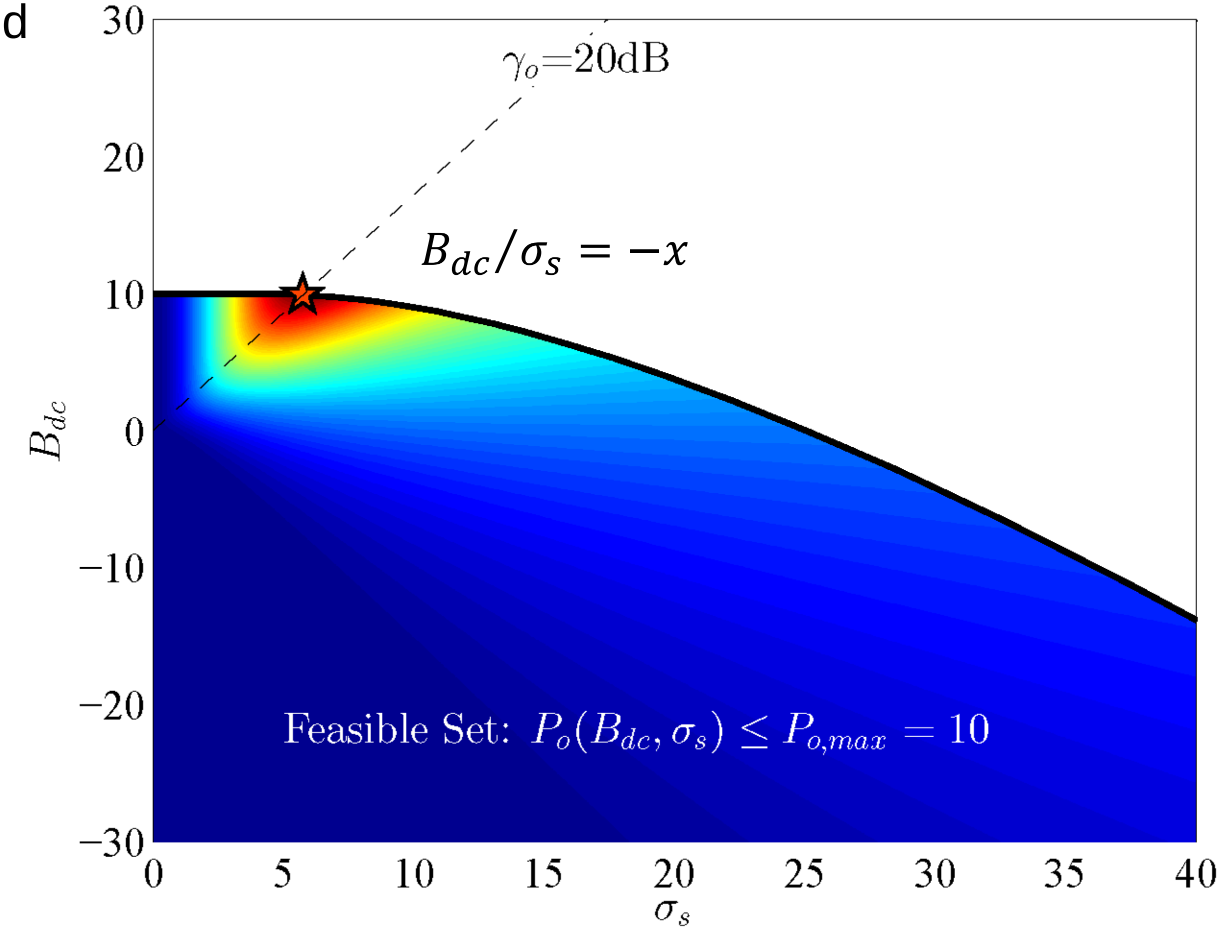
$\text{SNDR}_o(x)$ is a **quasiconcave** function of $x$. The optimization problem admits a **unique optimal solution** given by

$$x_o^\star = arg_x\, f_o(x) = 0.$$

- $f_o(x) = (1-\gamma_o^{-1})\big(g(x) - xQ(x)\big) + x$ is a monotonically **increasing** function with the following properties:
  - If $\gamma_o > 1$, $f_o(x)$ is convex;
  - If $\gamma_o = 1$, $f_o(x)$ is linear;
  - If $\gamma_o < 1$, $f_o(x)$ is concave;
- The optimal IC-power $\sigma_s^\star = P_{o,\max}/p_o(x_o^\star)$
- The optimal DC-offset $\boldsymbol{B_{dc}^\star = P_{o,max}(1-\gamma_o^{-1})}$ in **closed form.**

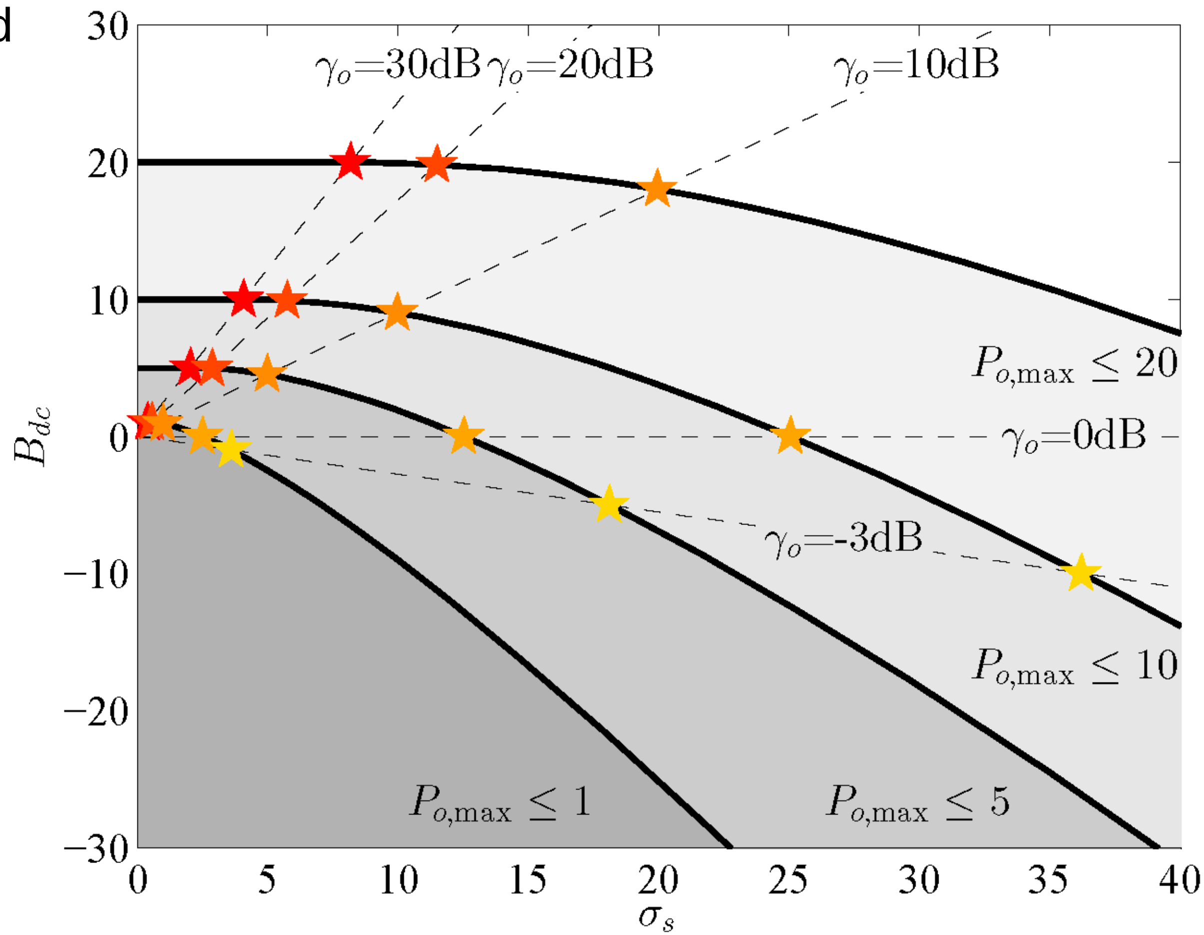
# Signal Shaping Optimization

- The given DC-offset and IC-power **is globally optimal** indeed.



# Signal Shaping Optimization

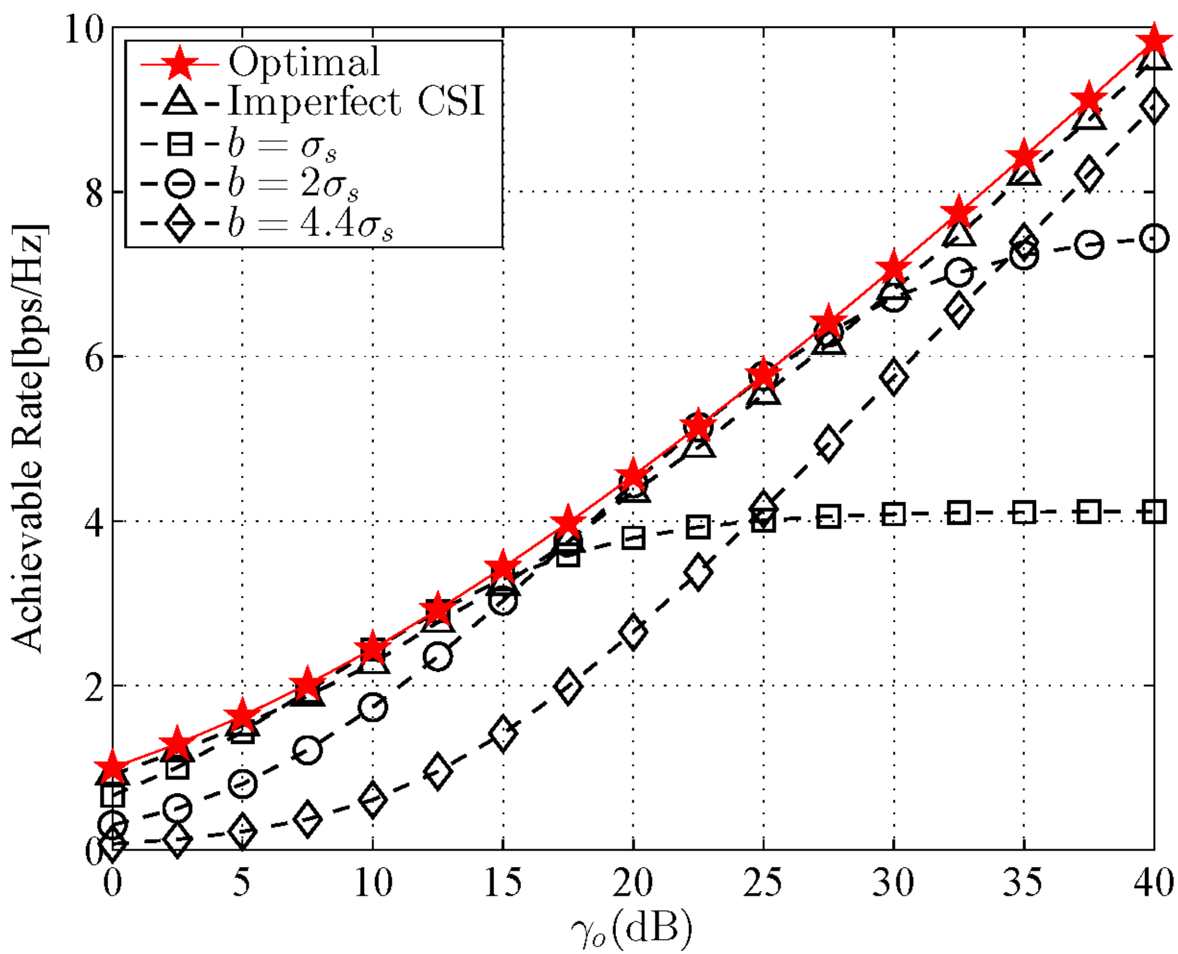
- The given DC-offset and IC-power is **globally optimal** indeed.
- $b^\star$ is **increasing** in $\gamma_o$; $\sigma_s^\star$ is **decreasing** in $\gamma_o$.
- A high DC-offset should be used at high SNR; a low DC-offset should be used at low SNR.
- $P_o(b^\star, \sigma_s^\star) = P_{o,\max}$, indicates **the illumination level is constant.**
- $x_o^\star$ only depends on $\gamma_o$, and is irrelevant to the power budget $P_{o,\max}$.



# Numerical Results

- Parameters:
  - $\gamma_o = |H|^2 P_{o,\max}^2/\sigma_n^2$
  - Number of subcarriers 2K = 128
  - AWGN
  - Target BER = $10^{-5}$
- The schemes
  - $b = 2\sigma_s$
  - $b = 4.4\sigma_s$

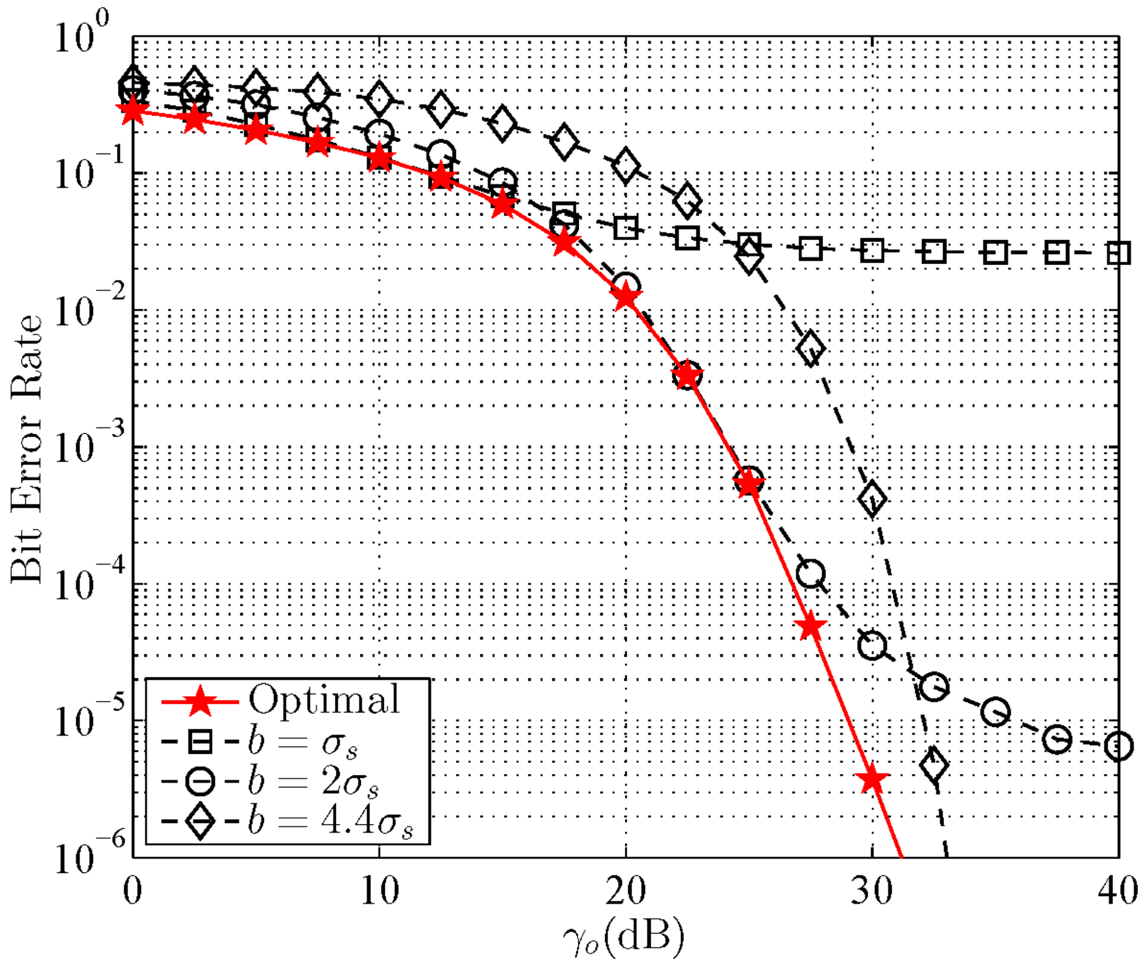
  correspond to 7dB and 13dB DC-offset defined in [Armstrong'CL2008]



# Simulation Results

- Parameters:
  - $\gamma_o = |H|^2 P_{o,\max}^2/\sigma_n^2$
  - Number of subcarriers 2K = 128
  - AWGN
  - 16QAM
- The schemes
  - $b = 2\sigma_s$
  - $b = 4.4\sigma_s$

  correspond to 7dB and 13dB DC-offset defined in [Armstrong'CL2008]

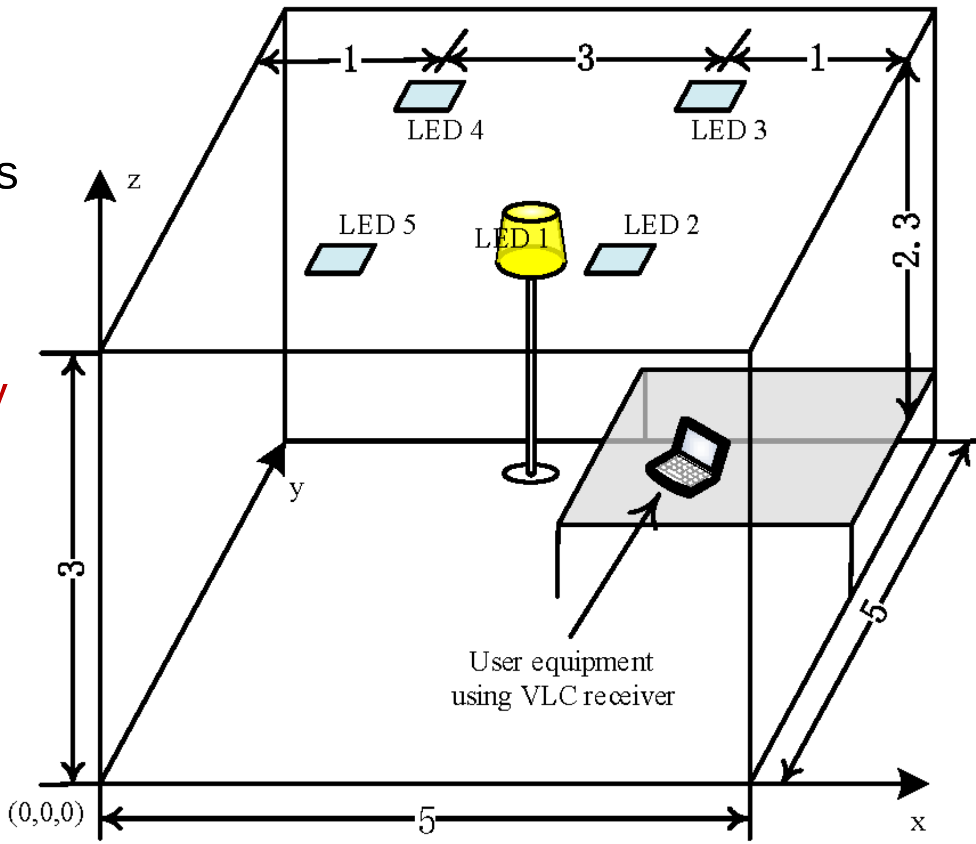


# Outline

1. Introduction
2. Optimal Signal Shaping for Single LED
3. **Optimal Biased Beamforming for Multi-LED**
4. Recent Advances
5. Conclusions

# Multi-LED VLC

- Multi-LED VLC
  - Distributed illumination light sources
  - Seamless coverage for both communication & illumination
  - Higher SNR & better service quality
  - Robust to blockage and shadowing
  - Flexibility for dimming control




- Call for a **coordinated** multi-LED transmission design

# Motivation

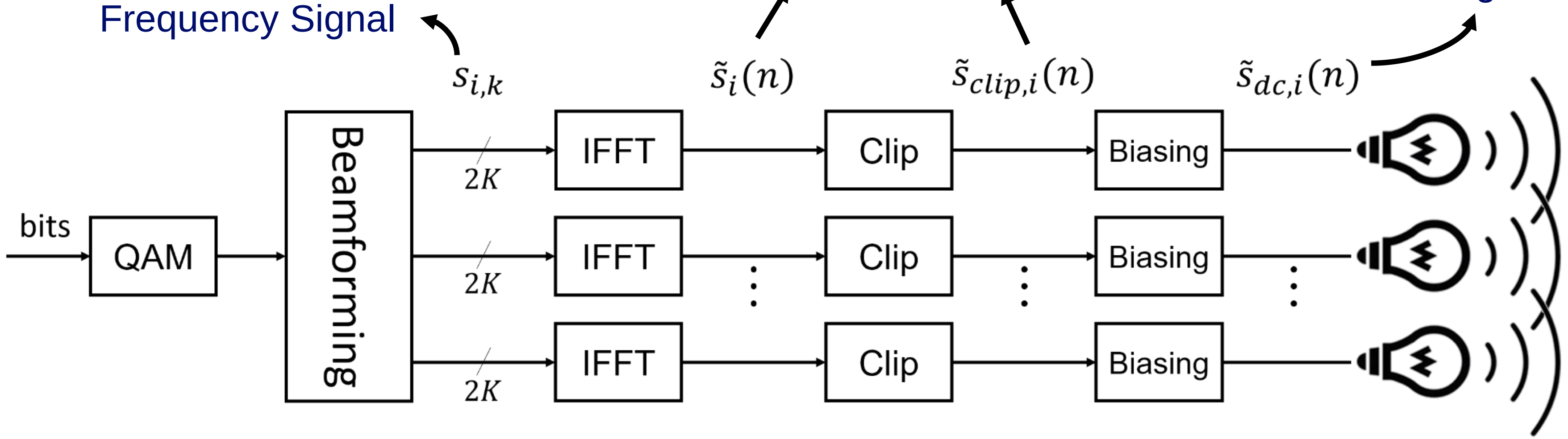
- **Motivation**
  - higher rates and better communication quality
  - Simple implementation for broadband applications
  - Seamless coverage for communication and illumination

- Multiple LEDs + Multicarrier ⇒ VLC
- **Questions:**
  - How to model the nonlinear clipping process?
  - How to design the beamforming vectors for all LEDs?
  - How to set the DC bias of each LED?
- **Biased Beamforming**:
  - Beamforming vectors $\mathbf{w}_k \triangleq \{w_{ik}\}$
  - DC bias $\boldsymbol{b} \triangleq \{b_i\}$
  - Information-Carrying power $\boldsymbol{\sigma} \triangleq \{\sigma_i\}$

} **Require a joint design**

# System Model

- DCO-OFDM Transmitter with Multiple LEDs




- VLC Channel model:

$$r_k = \mathbf{h}_k^H \mathbf{s}_{dc,k} + \eta_k,\ k = 1, \ldots, K-1$$

  – Flat channel (but the channels of each LED may be different)

  – Dispersive channel (See [Ling'JSAC2018] for details)

LEDs: $i = 1, \ldots, N$
Carriers: $k = 0, \ldots, 2K-1$
Effective Carriers: $k = 1, \ldots, K-1$
(Due to the Hermitian symmetry.)

# Optical Power

- Human-perceived brightness ⇒ average optical power
- Average optical power of LED *i*: $p_{o,i}(b_i,\sigma_i) = \mathbb{E}[\tilde{s}_{dc,i}(n)]$
  - A function of DC bias $b_i$ and information-carrying power $\sigma_i$
  - Usually, $p_{o,i}(b_i,\sigma_i) = \mathbb{E}[\tilde{s}_{dc,i}(n)] \neq b_i$ due to the asymmetric clipping
- The constant optical power constraint is due to
  - Illumination requirement
  - Dimming control
  - Eye protection
  - Power saving

  } $p_{o,i}(b_i,\sigma_i) = \bar{p}_{o,i}$ → $\bar{p}_{o,i}$ : some specific illumination level
- Per-LED optical power constraint:
  - $p_{o,i}(b_i,\sigma_i) = \bar{p}_{o,i} \quad i = 1, \ldots, N_t$
  - The vector version: $\mathbf{p}_o(\mathbf{b},\boldsymbol{\sigma}) = \bar{\mathbf{p}}_o$ → $\mathbf{p}_o(\mathbf{b},\boldsymbol{\sigma}) \triangleq \{p_{o,i}(b_i,\sigma_i)\}_{i=1}^{N_t}$: the optical power of each LED

# Biased Beamforming Design

Optimization variables:

- $\mathbf{b}$: DC-bias vector
- $\boldsymbol{\sigma}$: Information-Carrying power (i.e., useful power)
- $\{\mathbf{w}_k\}$: beamforming vector

Objective: Maximize the sum rate of effective subcarriers

**Difficulty 1:**
the expression of rate is unclear (due to the nonlinear clipping)

$$\underset{\mathbf{b},\boldsymbol{\sigma},\{\mathbf{w}_k\}}{\text{maximize}} \quad R=\sum_{k=1}^{K-1} R_k$$

$$\text{subject to} \quad \mathbf{p}_o(\mathbf{b},\boldsymbol{\sigma})=\bar{\mathbf{p}}_o$$

Per-LED optical power constraint

$$\sigma_i^2=\frac{1}{K}\sum_{k=1}^{K-1}\left[\mathbf{w}_k\mathbf{w}_k^H\right]_{ii}, \quad i=1,\ldots,N_t$$

The relationship between IC-Power $\sigma_i$ and beamformer $\mathbf{w}_k$

# Nonlinear Clipping

- **Question**: what is the expression of rate *R*?
  - A model to characterize the nonlinear clipping process?
  - The relationship between the clipped signal $\mathbf{s}_{dc,k}$ and the original one $\mathbf{s}_k$?

- **Hint**: use a linear model to approximate the nonlinear clipping process

- For a single LED, the clipping model based on the Bussgang theorem in the frequency domain [Dimitrov'TCOM12], [Chen'TCOM2012]:

$$s_{dc,k} = a s_k + n_{clip,k}, \qquad k = 1, \ldots, K-1$$

  - A linear attenuation factor $a$
  - The clipping noise $n_{clip,k}$ uncorrelated with the signal $s_k$
  - The clipping noise is approximated to a Gaussian distribution when the number of subcarriers is large
- **Question**: What if Multi-LEDs?

# Clipping Model for multi-LEDs

Generalized Bussgang theorem for multiple LEDs

**Theorem 2 (Multi-LED Clipping Model)**

The time-domain clipping process of multi-LEDs can be modeled in frequency domain as

$$\mathbf{s}_{dc,k} = \mathbf{A}\mathbf{s}_k + \mathbf{n}_{clip,k}, \qquad k = 1, \ldots, K-1$$

where $\mathbf{A}(\mathbf{b}, \boldsymbol{\sigma}) = \mathbf{Diag}(\mathbf{a}) = \mathbf{Diag}\{1 - Q(b_i/\sigma_i)\}_{i=1}^{N_t}$ contains the attenuation factors, and $\mathbf{n}_{clip,k}$ is the vector of clipping noise obeying $\mathcal{CN}(\mathbf{0}, \mathbf{C}(\mathbf{b}, \boldsymbol{\sigma}))$. (Please see Theorem 1 in [Ling'JSAC2018] for details.)

- A linear attenuation matrix $\mathbf{A}(\mathbf{b}, \boldsymbol{\sigma})$
- The vector of clipping noise $\boldsymbol{n}_{clip,k}$ uncorrelated with the signal $\mathbf{s}_k$
- The Gaussian approximation is still available
- The clipping noises from multiple LEDs are **mutually correlated**
- Each term in covariance matrix $\mathbf{C}(\mathbf{b}, \boldsymbol{\sigma})$ is a **piecewise function** of $\mathbf{b}$ and $\boldsymbol{\sigma}$

# Effective SNR (SNDR)

- Simplified the frequency-domain signal model: $\eta_k$: Background Noise

$$r_k = \mathbf{h}_k^H \mathbf{s}_{dc,k} + \eta_k$$
$$= \mathbf{h}_k^H (\mathbf{A}\mathbf{s}_k + \mathbf{n}_{clip,k}) + \eta_k$$
$$= \mathbf{h}_k^H \mathbf{A}\mathbf{s}_k + \mathbf{h}_k^H \mathbf{n}_{clip,k} + \eta_k$$

$\mathbf{h}_k$: Channel frequency response

Via the clipping model in Thoerem 1

- **SNDR** (signal-to-noise-plus-distortion ratio) at subcarrier $k$:

$$\text{SNDR}_k \triangleq \frac{\text{Effective Signal Power}}{\text{Clipping Noise Power} + \text{Background Noise Power}}$$
$$= \frac{\mathbf{h}_k^H \mathbf{A}(\mathbf{b},\sigma)\mathbf{w}_k \mathbf{w}_k^H \mathbf{A}(\mathbf{b},\sigma)\mathbf{h}_k}{\mathbf{h}_k^H \mathbf{C}(\mathbf{b},\sigma)\mathbf{h}_k + \sigma_\eta^2}$$

$\mathbf{C}(\mathbf{b}, \boldsymbol{\sigma})$: Clipping noise covariance

$\mathbf{A}(\mathbf{b}, \boldsymbol{\sigma})$: Linear attenuation matrix

- Achievable rate at subcarrier $k$:

$$R_k = \log(1 + \text{SNDR}_k)$$

# Biased Beamforming Problem

Optimization variables:

- $\mathbf{b}$: DC-bias vector
- $\boldsymbol{\sigma}$: Information-Carrying power (i.e., useful power)
- $\{\mathbf{w}_k\}$: beamforming vector

Objective: Maximize sum rate of effective subcarriers

**Difficulty 2:** the objective is nonconvex and highly nonlinear.

**Difficulty 3:** joint design

$$\underset{\mathbf{b},\boldsymbol{\sigma},\{\mathbf{w}_k\}}{\text{maximize}} \quad R=\sum_{k=1}^{K-1}\log\left(1+\frac{\mathbf{h}_k^H\mathbf{A}(\mathbf{b},\boldsymbol{\sigma})\mathbf{w}_k\mathbf{w}_k^H\mathbf{A}(\mathbf{b},\boldsymbol{\sigma})\mathbf{h}_k}{\mathbf{h}_k^H\mathbf{C}(\mathbf{b},\boldsymbol{\sigma})\mathbf{h}_k+\sigma_\eta^2}\right)$$

$$\text{subject to} \quad \mathbf{p}_o(\mathbf{b},\boldsymbol{\sigma})=\bar{\mathbf{p}}_o$$

Per-LED optical power constraint

$$\sigma_i^2=\frac{1}{K}\sum_{k=1}^{K-1}\left[\mathbf{w}_k\mathbf{w}_k^H\right]_{ii},\quad i=1,\ldots,N_t$$

The relationship between IC-Power $\sigma_i$ and beamformer $\mathbf{w}_k$

# Optimal Beamformer

- **Hint**: search the optimal beamformer for fixed DC bias first.

- In this case, the optimal beamforming structure can be analytically characterized.
- Please see **Theorem 2** in [Ling'JSAC2018] for details.

- **Remarks**:
  – The optimal beamforming structure in [Ling'JSAC2018] is suitable for both flat and dispersive channels.
  – The **uniform beamforming** is **optimal** for flat channels.
  – The optimal beamforming tends to be **uniform** at high SNR for dispersive channels.

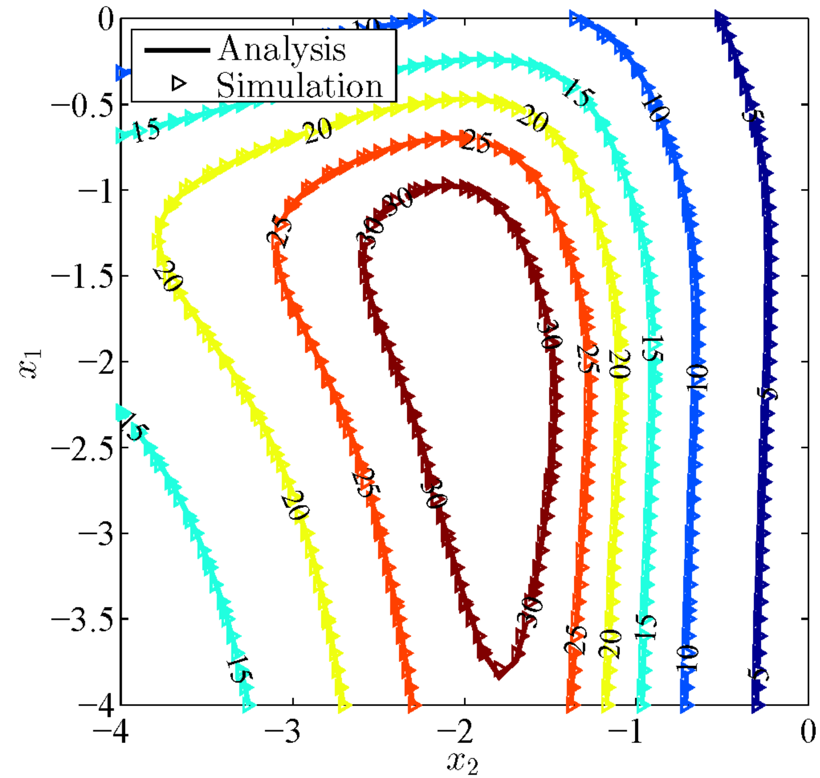
- **Question**: How to set the bias?

# Optimal Bias: Flat Channels

- Using the uniform beamforming.
- Normalized DC bias $\mathbf{x}$: $x_i \triangleq -b_i/\sigma_i$
  - –Vector form: $\mathbf{x} \triangleq \{x_i\}_{i=1}^{N_t} = -\mathbf{Diag}^{-1}(\sigma)\mathbf{b}$
- Reduce the dimensions and reformulate the problem as an **unconstrained** problem by using the normalized DC bias $\mathbf{x}$:

$$\underset{\mathbf{x}}{\text{maximize}} \quad \text{SNDR}(\mathbf{x})$$

- Notice: some super level sets are nonconvex ⇒
- **Nonconvex** problem, even simplified.
- **Still difficult!**




A two-LED simulation case with different normalized DC bias pairs.

# Optimal Bias: Flat Channels

The optimal DC bias can be analytically characterized for flat channels.

**Theorem 3 (Optimal Biased Beamforming)**

There exists a unique optimal solution $\mathbf{x}^\star = x^\star \cdot \mathbf{1}$, where $x^\star$ is the root of a monotone function $f(x;\gamma_t)$ and $\gamma_t$ is the total optical SNR. All the components of optimal solution are identical.

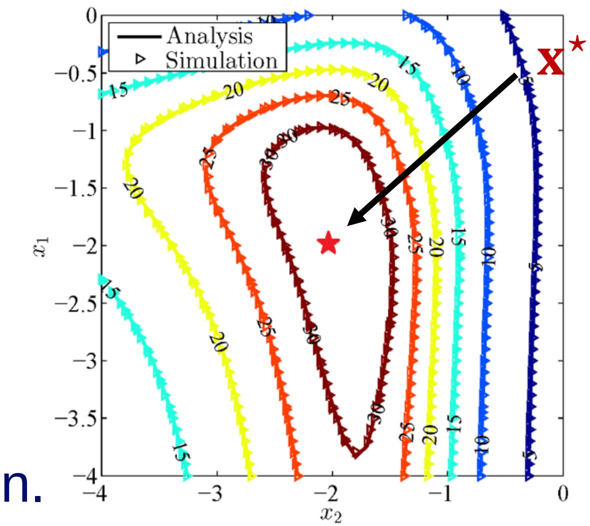
– $\mathbf{x}$ is the vector of the normalized DC bias.

– A **SURPRISE** results: The optimal normalized DC bias of each LED is **IDENTICAL**!

– Only hold for flat channels.

– As the root of a monotone function, $x^\star$ can be found via the Newton method.

– Identical bias setting is easy for implementation.



# Optimal Biased Beamforming

Closed-form biased beamforming in flat channels

## Corollary 1

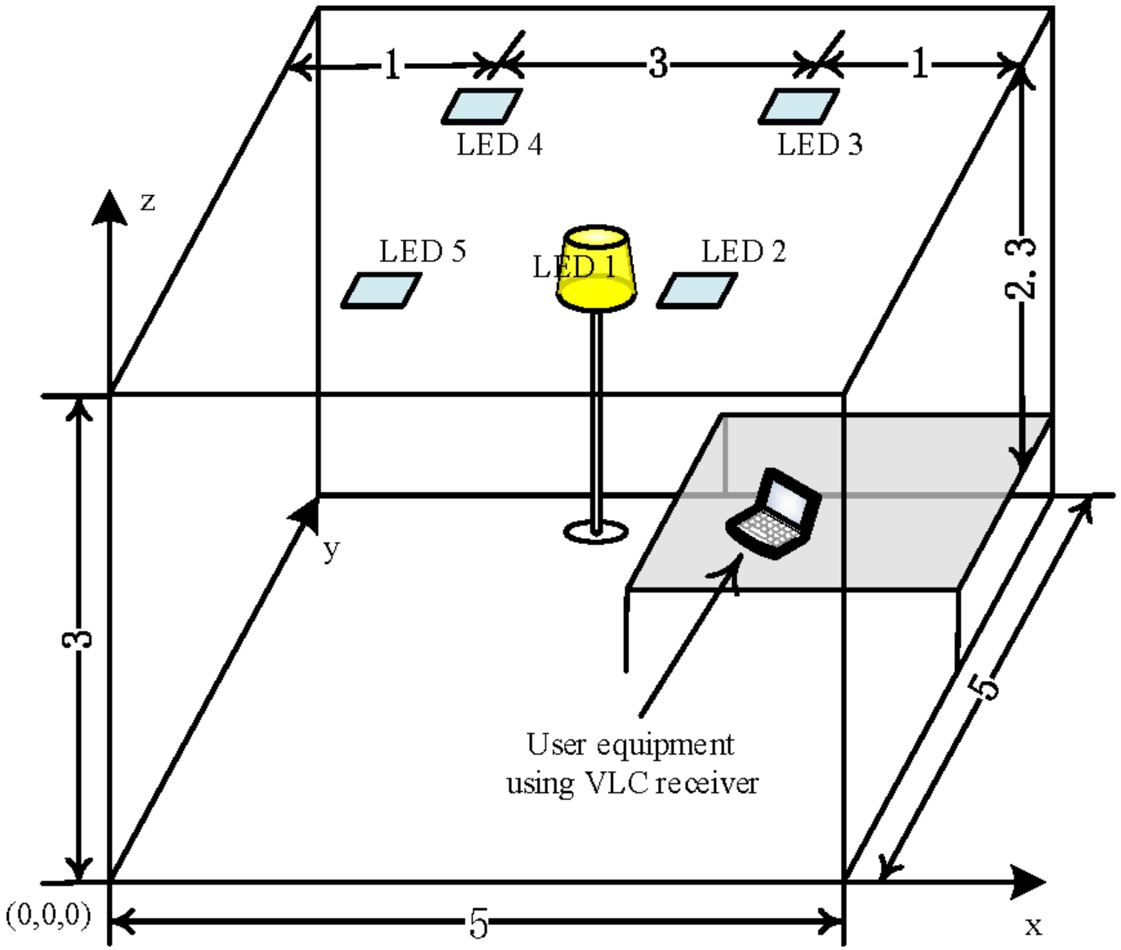
- The optimal DC bias is $\mathbf{b}^{\star} = \bar{\mathbf{p}}_{\boldsymbol{o}}(1 - \gamma_t^{-1})$.
- The optimal beamforming vectors are $\{\mathbf{w}_k^{\star}\} = \boldsymbol{\sigma}^{\star} = \frac{\mathbf{1}}{q_{\boldsymbol{o}}(x^{\star})}\bar{\mathbf{p}}_{\boldsymbol{o}}$.

- The optimal bias grows with optical SNR $\gamma_t$.
- The optimal IC power decreases with optical SNR $\gamma_t$.
- At high SNR, the clipping noise becomes the dominant factor that calls for a high DC bias.
- At low SNR, the background noise is the major distortion that calls for more IC power on effective signal.

$\gamma_t$: Total optical SNR;
$\bar{\mathbf{p}}_{\boldsymbol{o}}$: required illumination levels for each LED;
$x^{\star}$: the optimal $x$ revealed in Theorem 3.

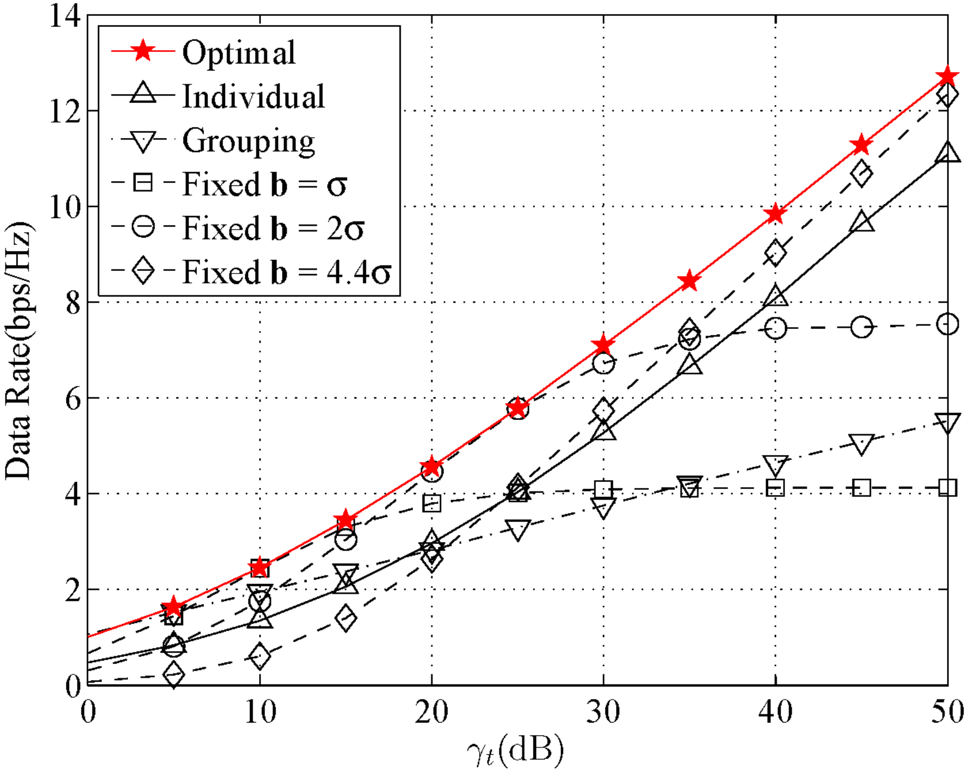
# Simulation Scenario

- Configuration of the multi-LED DCO-OFDM system adopted in simulation.



# Simulation Results (Rate)

- Parameters:
  - –Flat Channel;
  - –Channel bandwidth:100MHz;
  - –The number of total subcarriers: 2K=512;
- Schemes:
  - –"**Optimal**": the proposed optimal biased beamforming;
  - –"**Individual**": applying the optimal bias derived for a single LED on each LED;
  - –"**Grouping**": a half subcarriers are active on LED 1 and the other half are active on LED 2;
  - –"**Fixed bias**": a pre-fixed bias level.



# Simulation Results (BER)

- Parameters:
  - –Flat Channel;
  - –Channel bandwidth:100MHz;
  - –The number of total subcarriers: 2K=512;
- Schemes:
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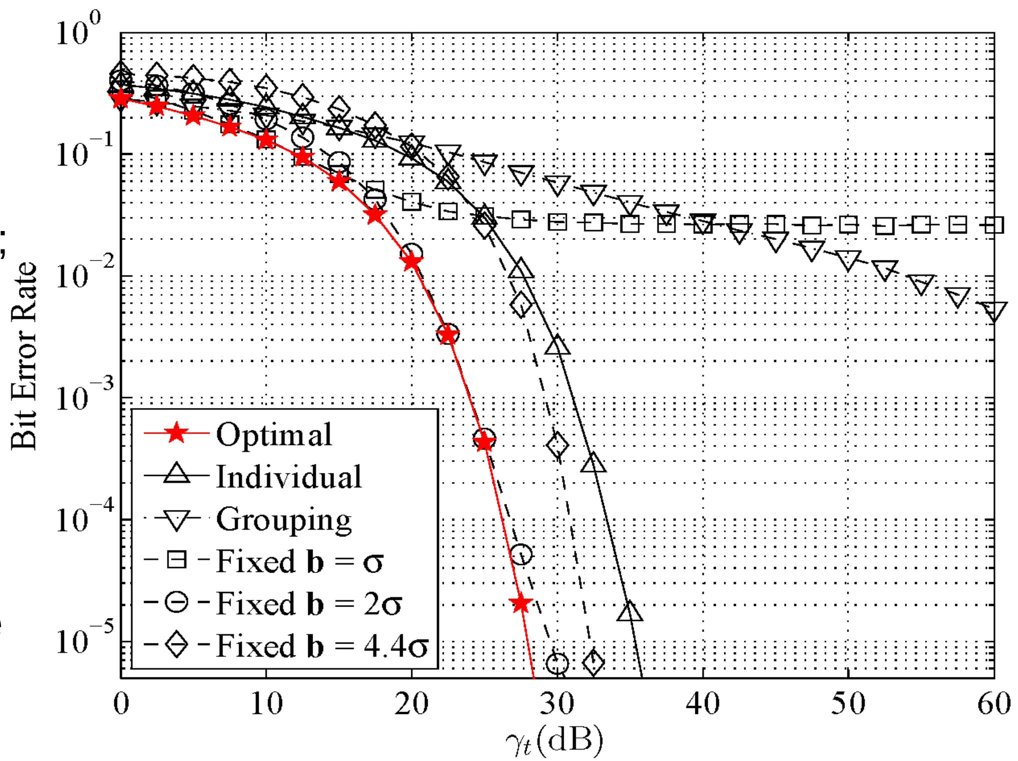
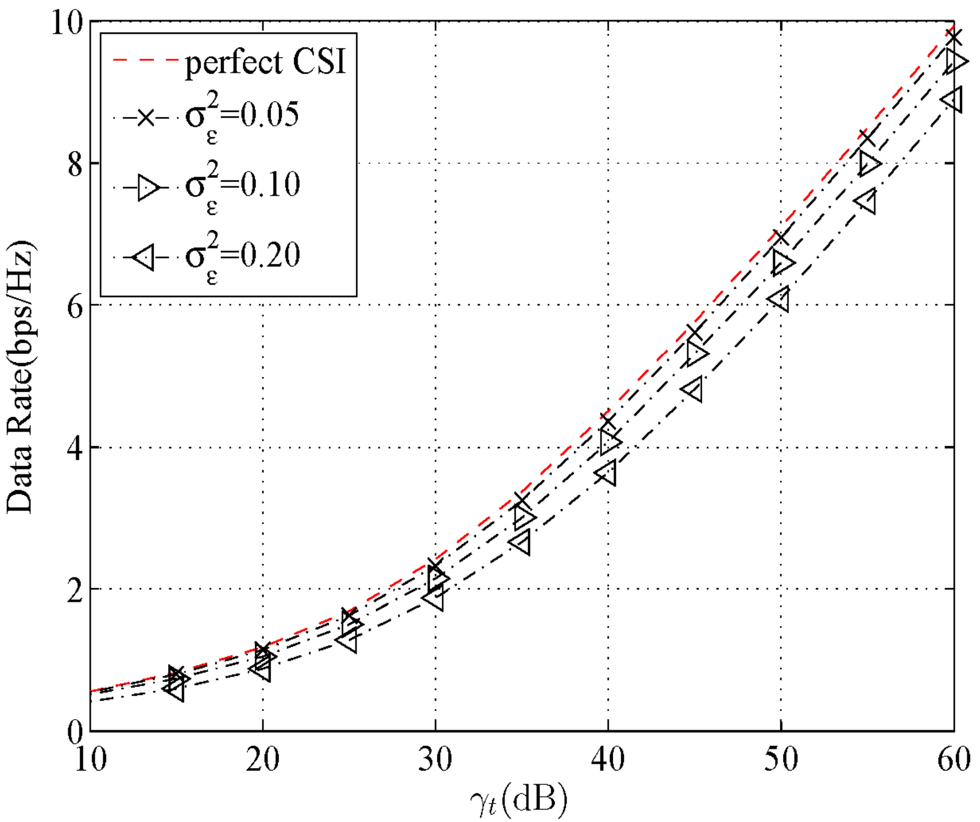


# Simulation Results (Sensitivity)

- **Parameters:**
  - –Dispersive Channel;
  - –Channel bandwidth:100MHz;
  - –The number of subcarriers: 2K=512;

- The channel coefficient here is no longer the actual $\mathbf{h}_k$ but $\mathbf{h}_k+\boldsymbol{\varepsilon}$, where the error $\boldsymbol{\varepsilon}$ follows an independent complex Gaussian distribution with variance $\sigma_\varepsilon^2$.

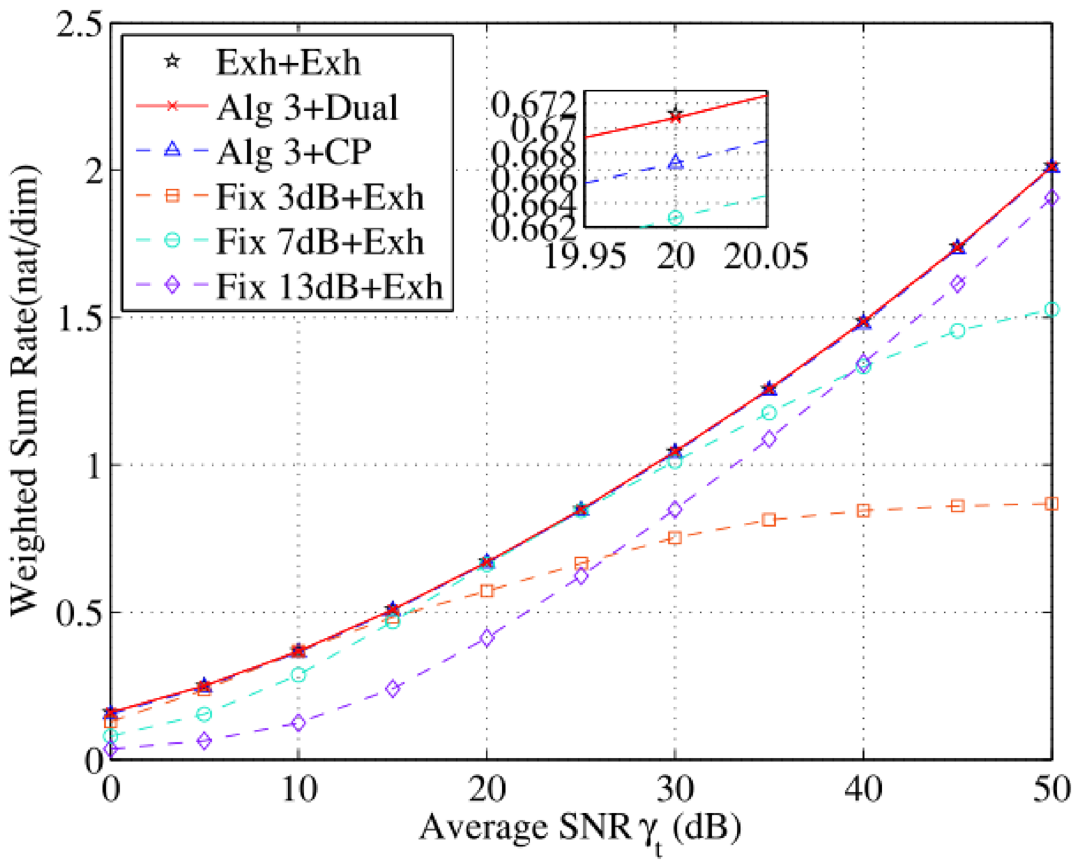


# Outline

1. Introduction
2. Optimal Signal Shaping for Single LED
3. Optimal Biased Beamforming for Multi-LED
4. **Recent Advances**
5. Conclusions

# DCO-OFDMA

- **What if there exist multiple users?**
- We proposed an iterative algorithm in [Ling'JLT2018].



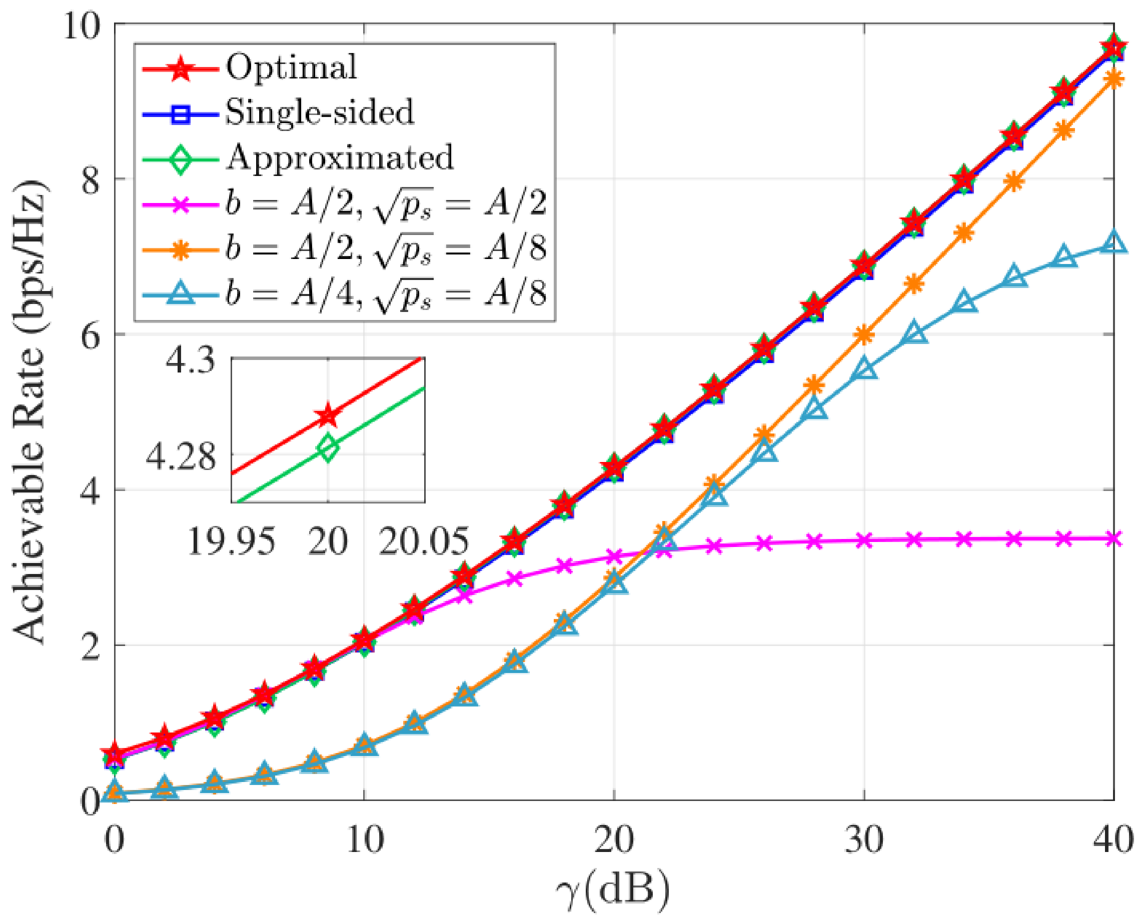
# Upper Clipping

- **What about the impact of upper clipping?**

$$s_{clip,n} = \mathrm{clip}\left[s_n + b; A\right] = \begin{cases} A & s_n + b \geq A \\ s_n + b & 0 < s_n + b < A \\ 0 & s_n + b \leq 0 \end{cases}$$

- This problem is also solved in [Ling'OE2020].
- The bias should be set to the midpoint of the dynamic range.
- We can also obtain an optimal power, given by the unique root of an increasing function.

# Upper Clipping

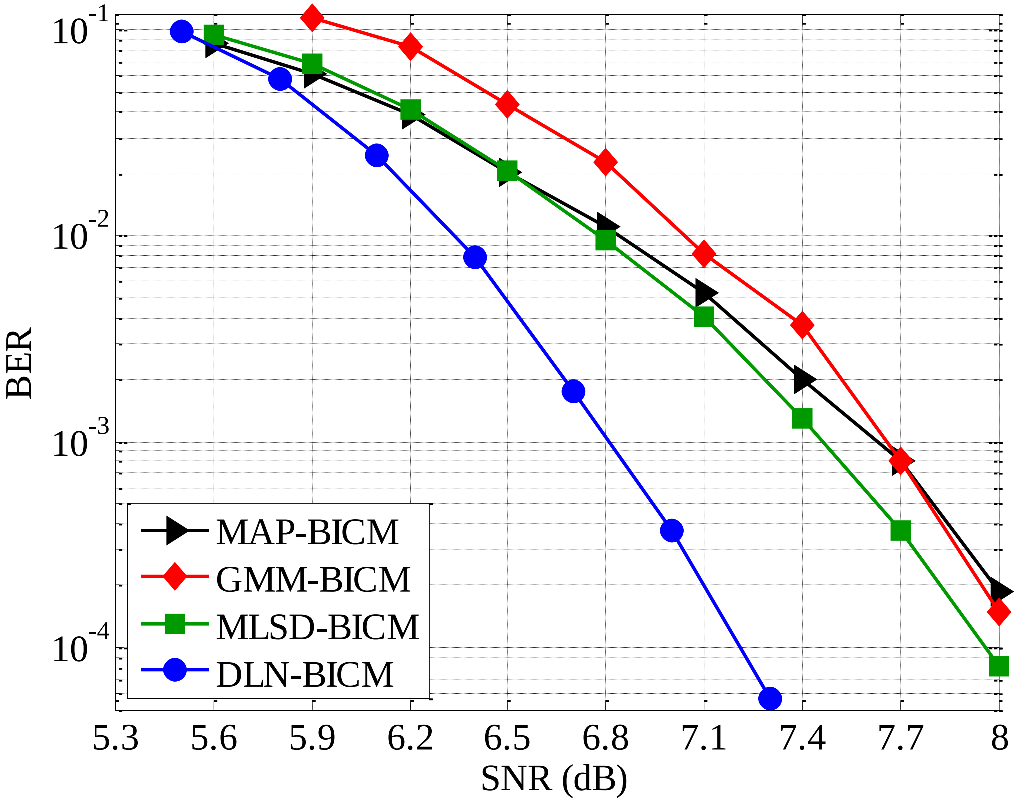


# Coding System

- Deep-Learning-Network-based BICM [He'TCOM2020]

Simulation Parameters:

- DLN-BICM
- LDPC code
- 16QAM
- 1024subcarrier




- **Effective to mitigate nonlinear distortion in VLC.**

# Outline

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# Conclusions

- The **signal shaping design** is vital to IM/DD VLC.
- The single-LED system:
  - We **jointly optimize** the **DC bias** and **power**;
  - We obtain a **globally optimal solution** to the shaping design.
- The multi-LED system:
  - We introduce the concept of **biased beamforming**, a joint design of beamforming, DC bias, and IC power;
  - We analyze the clipping process for multi-LED VLC;
  - We find the optimal beamforming structure;
  - We achieve the **globally optimal biased beamforming**.
- The existence of upper clipping.
- The multi-user VLC system (DCO-OFDMA).
- The dispersive case is more complex and requires efficient methods.
- More effective receiving algorithms are called.

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# THE END

# THANKS!

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