川渝前沿论坛（第四期）

本期主题：可见光通信与定位

重庆大学 CHONGQING UNIVERSITY

智能LiFi实验室 Lab of Intelligent LiFi

重庆大学 微电子与通信工程学院 CHONGQING UNIVERSITY SCHOOL OF MICROELECTRONICS AND COMMUNICATION ENGINEERING

可见光通信物理层传输技术研究现状和发展趋势

川渝前沿论坛（第四期）

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报告大纲

智能LiFi实验室
Lab of Intelligent LiFi

- 可见光通信（VLC）简介
- VLC物理层传输关键技术概述
- VLC物理层调制与复用技术
- VLC物理层MIMO传输技术
- VLC物理层多用户接入技术
- 总结与展望

可见光通信（VLC）简介

智能LiFi实验室
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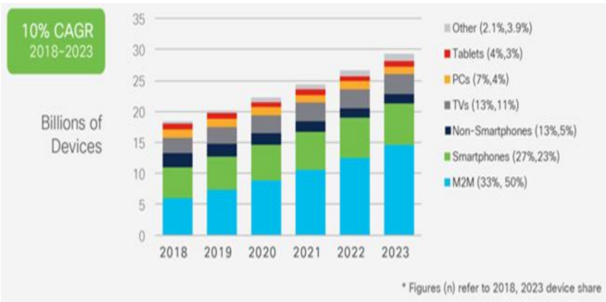
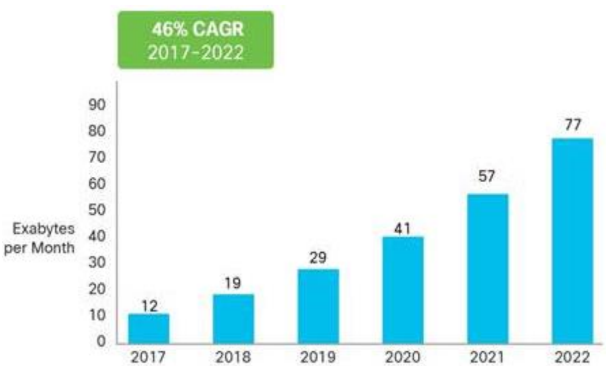
既有“射频无线，如4G/5G和WiFi等”，何须“VLC”？

更多设备，更大流量

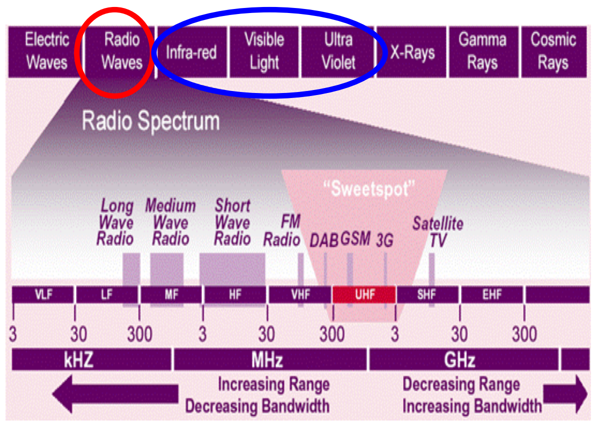


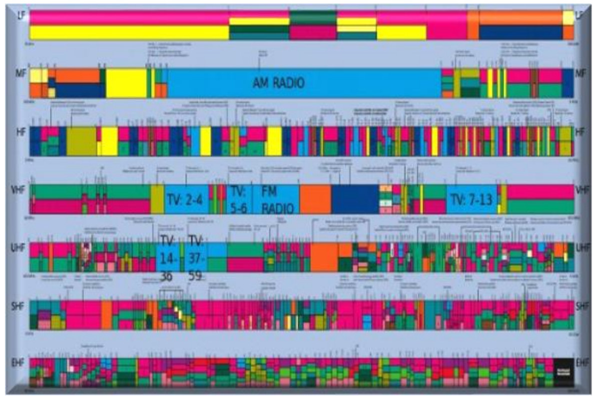


◆从2018到2023年，用户设备数量以10%的复合年增长率高速增长

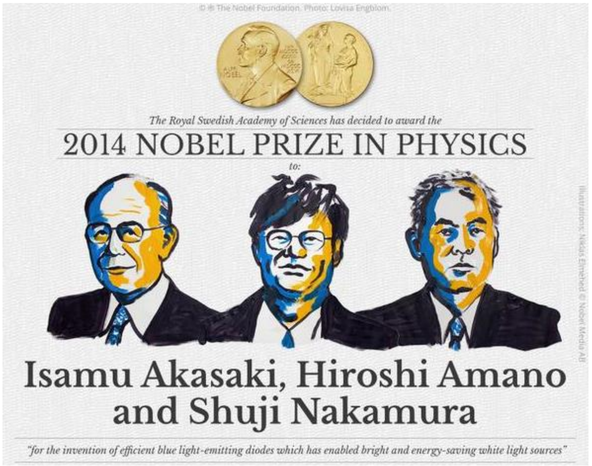
◆从2017到2022年，移动数据流量以46%的复合年增长率高速增长

射频短缺，光谱无限





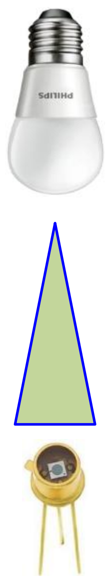
携手照明，应运而生



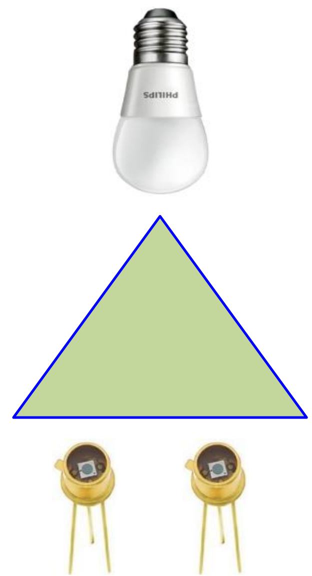
Cisco Annual Internet Report (2018–2023) White Paper.
Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017–2022.

VLC物理层传输关键技术概述

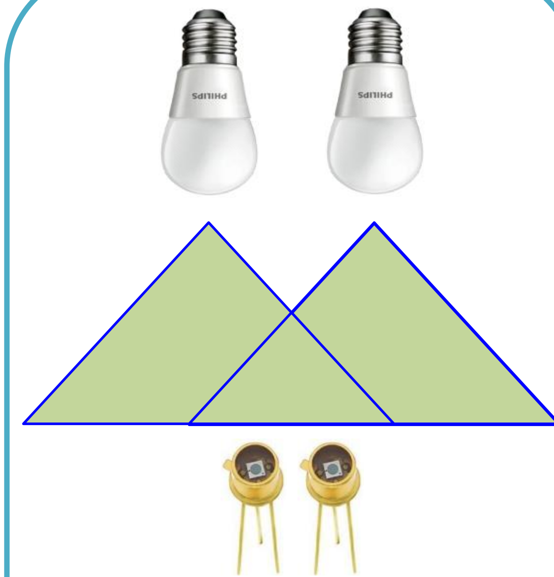
VLC物理层常见传输模式



点对点传输



点对多点传输



多点对多点传输

调制与复用

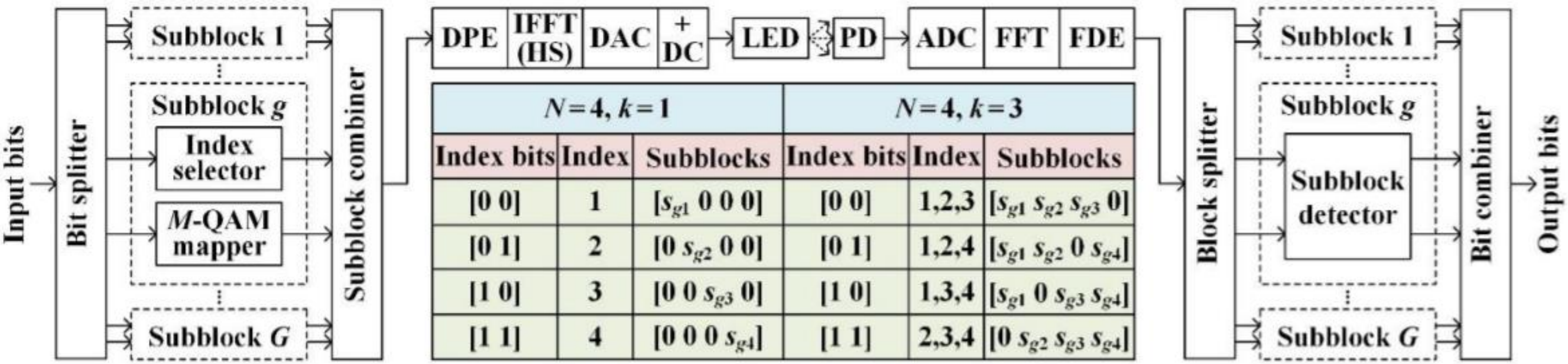
多用户接入

MIMO传输

VCL物理层常用调制（复用）技术

		优点	缺点
单载波调制	OOK	复杂度低	一维二进制 频谱效率低
	M-PAM	复杂度较低 频谱效率高	一维多进制 SNR要求高
多载波调制	OFDM	频谱效率高 对抗低通多径	复杂度较高 PAPR高
	M-CAP	频谱效率高 PAPR较低	复杂度较高 受低通影响

OFDM-IM: a combination of OFDM and index modulation (IM)



$N=4, k=1$			$N=4, k=3$		
Index bits	Index	Subblocks	Index bits	Index	Subblocks
[0 0]	1	$[s_{g1}\ 0\ 0\ 0]$	[0 0]	1,2,3	$[s_{g1}\ s_{g2}\ s_{g3}\ 0]$
[0 1]	2	$[0\ s_{g2}\ 0\ 0]$	[0 1]	1,2,4	$[s_{g1}\ s_{g2}\ 0\ s_{g4}]$
[1 0]	3	$[0\ 0\ s_{g3}\ 0]$	[1 0]	1,3,4	$[s_{g1}\ 0\ s_{g3}\ s_{g4}]$
[1 1]	4	$[0\ 0\ 0\ s_{g4}]$	[1 1]	2,3,4	$[0\ s_{g2}\ s_{g3}\ s_{g4}]$

Principle of IM/DD VLC using OFDM-IM

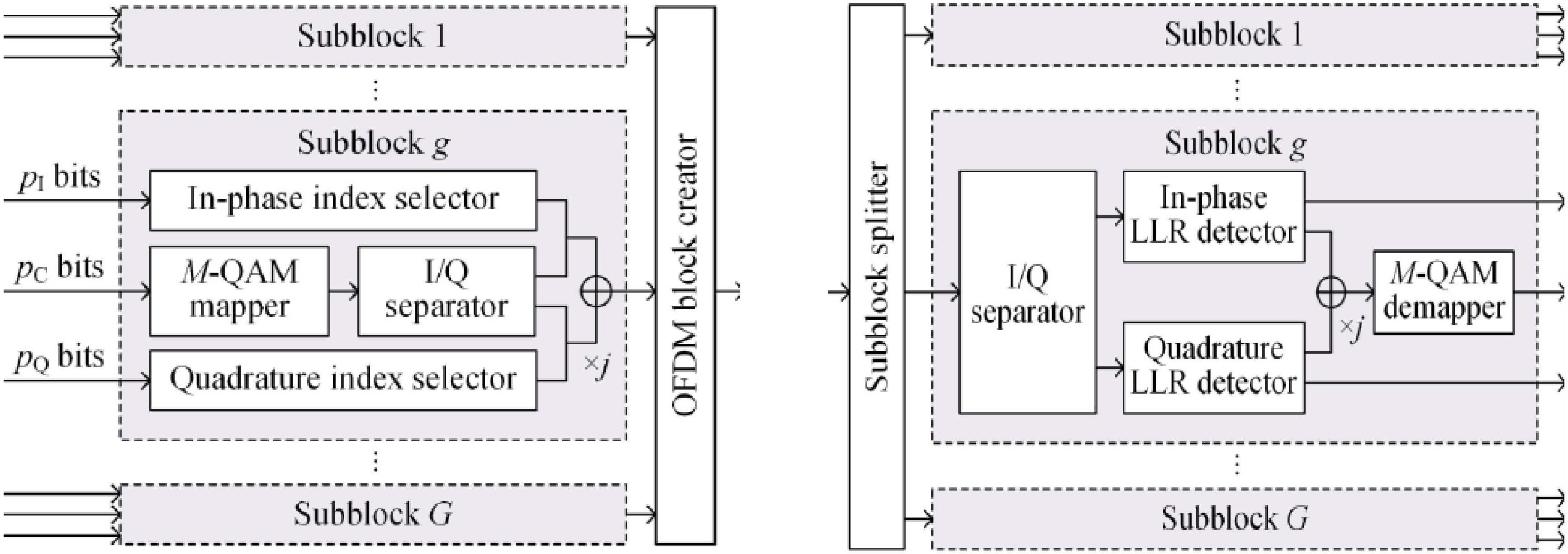
Assuming selecting *k* out *N* subcarrier for IM with *M*-QAM constellation,

$$SE_{IM} = \frac{\lfloor \log_2(C(N,k)) \rfloor + k\log_2(M)}{N}$$

- **OFDM-IM can be more power efficient than OFDM**
- **OFDM-IM can achieve a finer-grained SE, such as 1.5 bits/s/Hz**

C. Chen*, et al., "Experimental demonstration of optical OFDM with subcarrier index modulation for IM/DD VLC," ACP, 2019.

OFDM-QIM: exploring both I and Q components for parallel IM



Assuming selecting *k* out *N* subcarrier for parallel IM with *M*-QAM constellation,

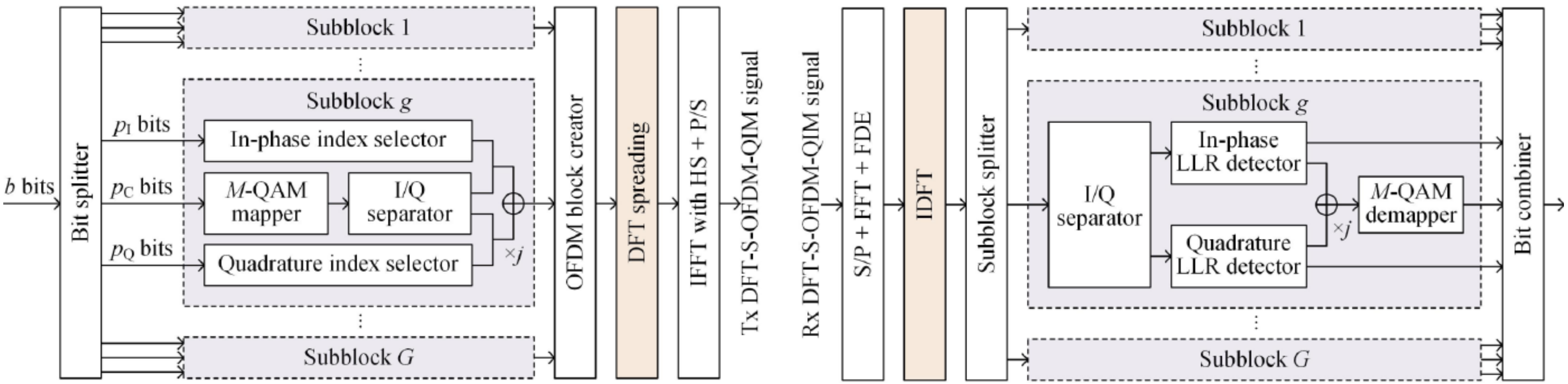
$$\mathrm{SE_{QIM}} = \frac{2\lfloor \log_2(C(N,k)) \rfloor + k\log_2(M)}{N}$$

OFDM-QIM can transmit double index bits than OFDM-IM

F. Ahmed, Y. G. Nie, **C. Chen***, et al., "DFT-spread OFDM with quadrature index modulation for practical VLC systems," Optics Express, 2021.

VLC物理层调制与复用技术

DFT-spread OFDM-QIM (DFT-S-OFDM-QIM) for VLC with nonlinearity



(a) DFT-S-OFDM-QIM transmitter (b) DFT-S-OFDM-QIM receiver

Low-complexity near-optimal log-likelihood ratio (LLR) detection is used:

$$\lambda_{g,\eta}^{\mathrm{I}} = \ln(k) - \ln(N-k) + \frac{\left|\mathrm{Re}(y_{g,\eta})\right|^2}{N_0} + \ln\left(\sum_{m=1}^{M^{\mathrm{I}}} \exp\left(-\frac{1}{N_0}\left|\mathrm{Re}(y_{g,\eta}) - s_m^{\mathrm{I}}\right|^2\right)\right)$$

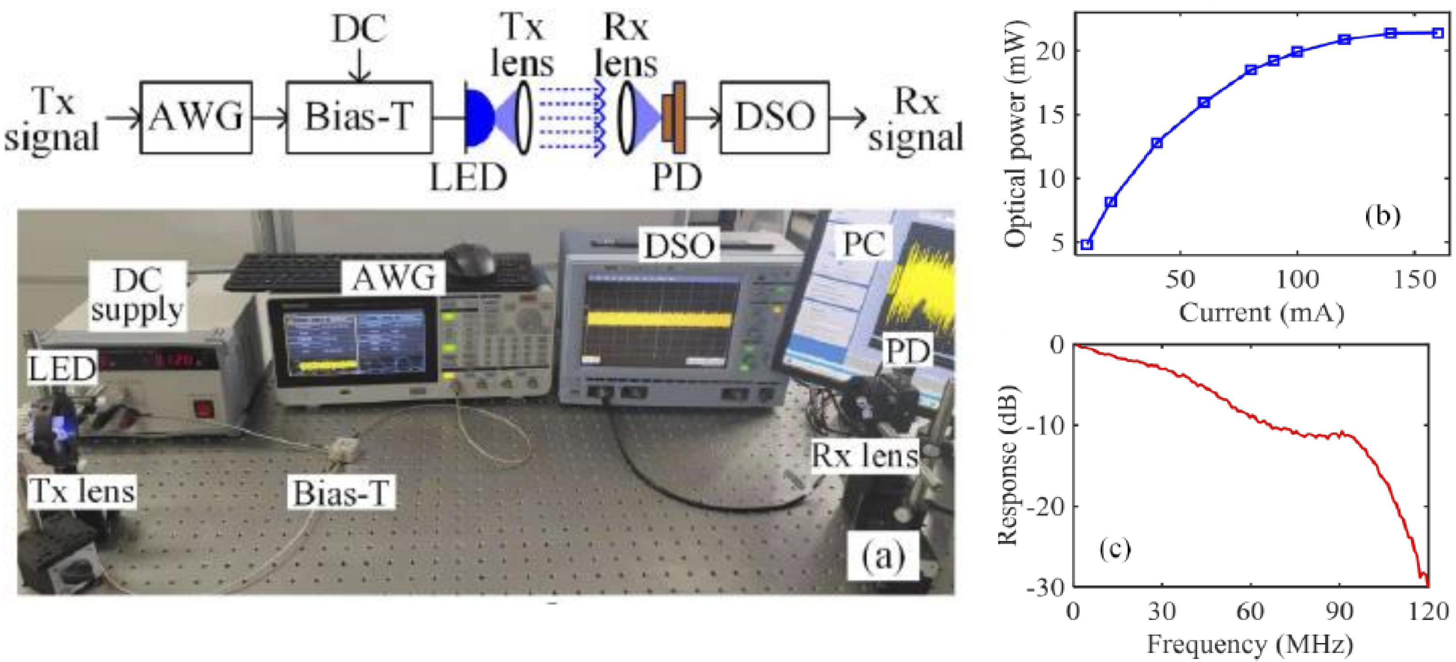
$$\lambda_{g,\eta}^{\mathrm{Q}} = \ln(k) - \ln(N-k) + \frac{\left|\mathrm{Im}(y_{g,\eta})\right|^2}{N_0} + \ln\left(\sum_{m=1}^{M^{\mathrm{Q}}} \exp\left(-\frac{1}{N_0}\left|\mathrm{Im}(y_{g,\eta}) - s_m^{\mathrm{Q}}\right|^2\right)\right)$$

F. Ahmed, Y. G. Nie, **C. Chen***, et al., "DFT-spread OFDM with quadrature index modulation for practical VLC systems," Optics Express, 2021.

System setup for simulation and experiments:

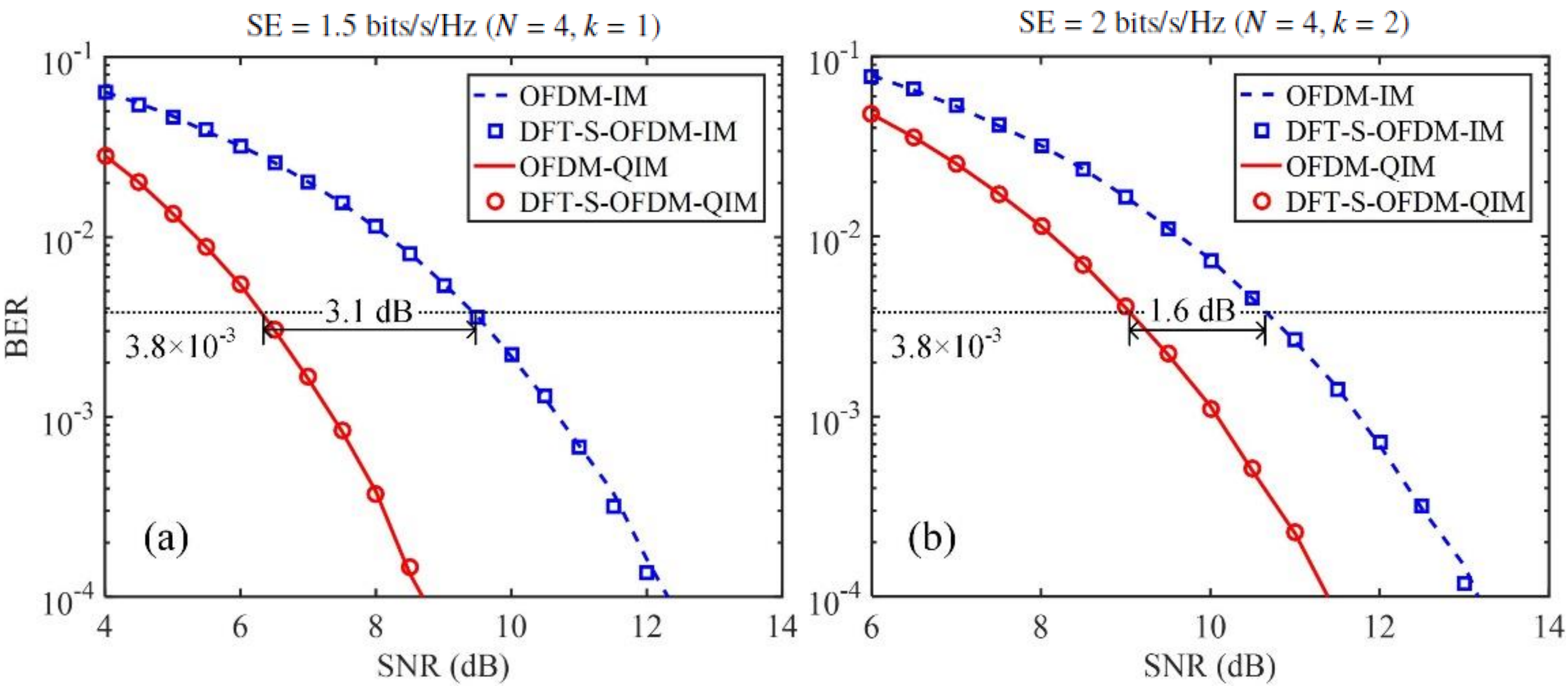
Table 1. Required *M*-QAM constellations to achieve a target SE for four schemes.

Scheme	SE = 1.5 bits/s/Hz (N = 4, k = 1)	SE = 2 bits/s/Hz (N = 4, k = 2)
OFDM-IM	16-QAM	8-QAM
DFT-S-OFDM-IM	16-QAM	8-QAM
OFDM-QIM	4-QAM	4-QAM
DFT-S-OFDM-QIM	4-QAM	4-QAM



F. Ahmed, Y. G. Nie, **C. Chen***, et al., "DFT-spread OFDM with quadrature index modulation for practical VLC systems," Optics Express, 2021.

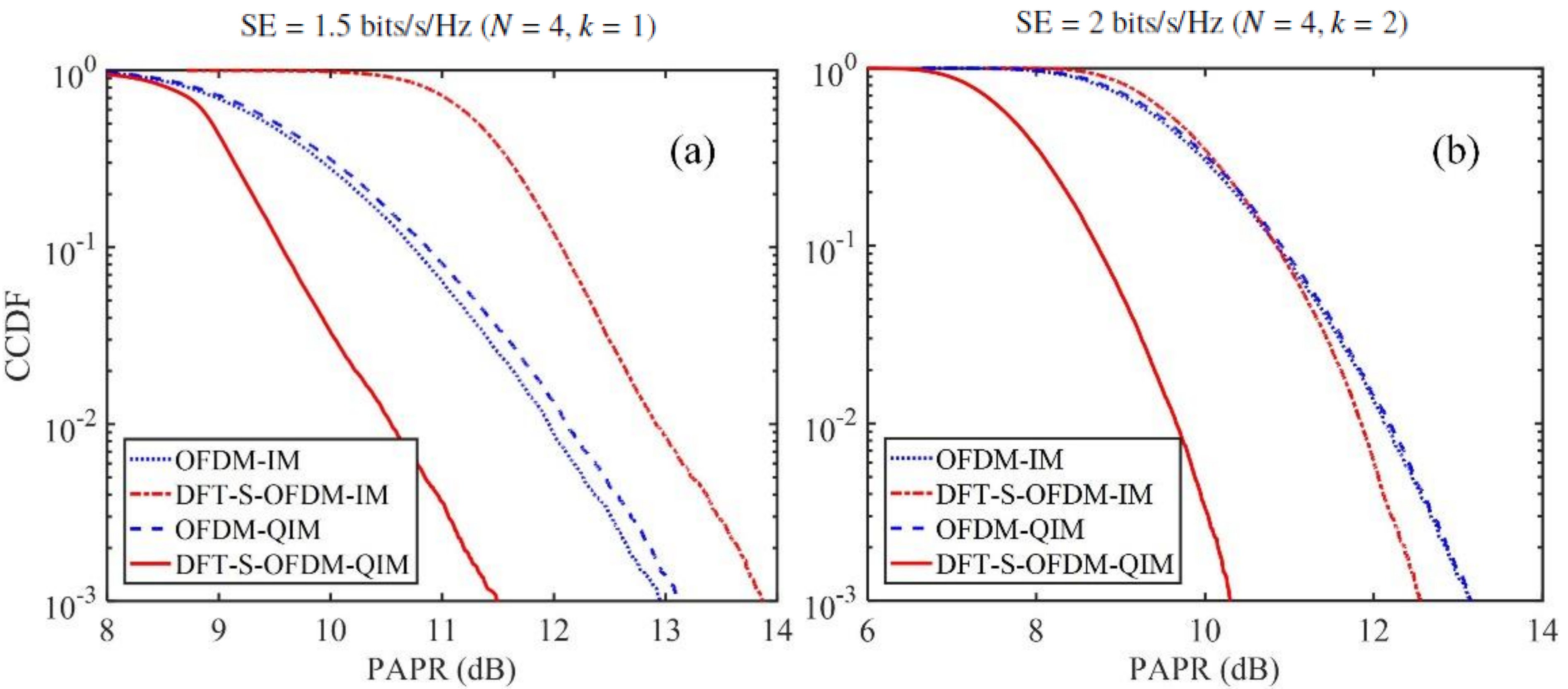
Simulation results:



- **OFDM-QIM achieves better BER than OFDM-IM for both *k* = 1, 2**
- **A larger SNR gain is obtained for a smaller *k***

F. Ahmed, Y. G. Nie, **C. Chen***, et al., “DFT-spread OFDM with quadrature index modulation for practical VLC systems,” Optics Express, 2021.

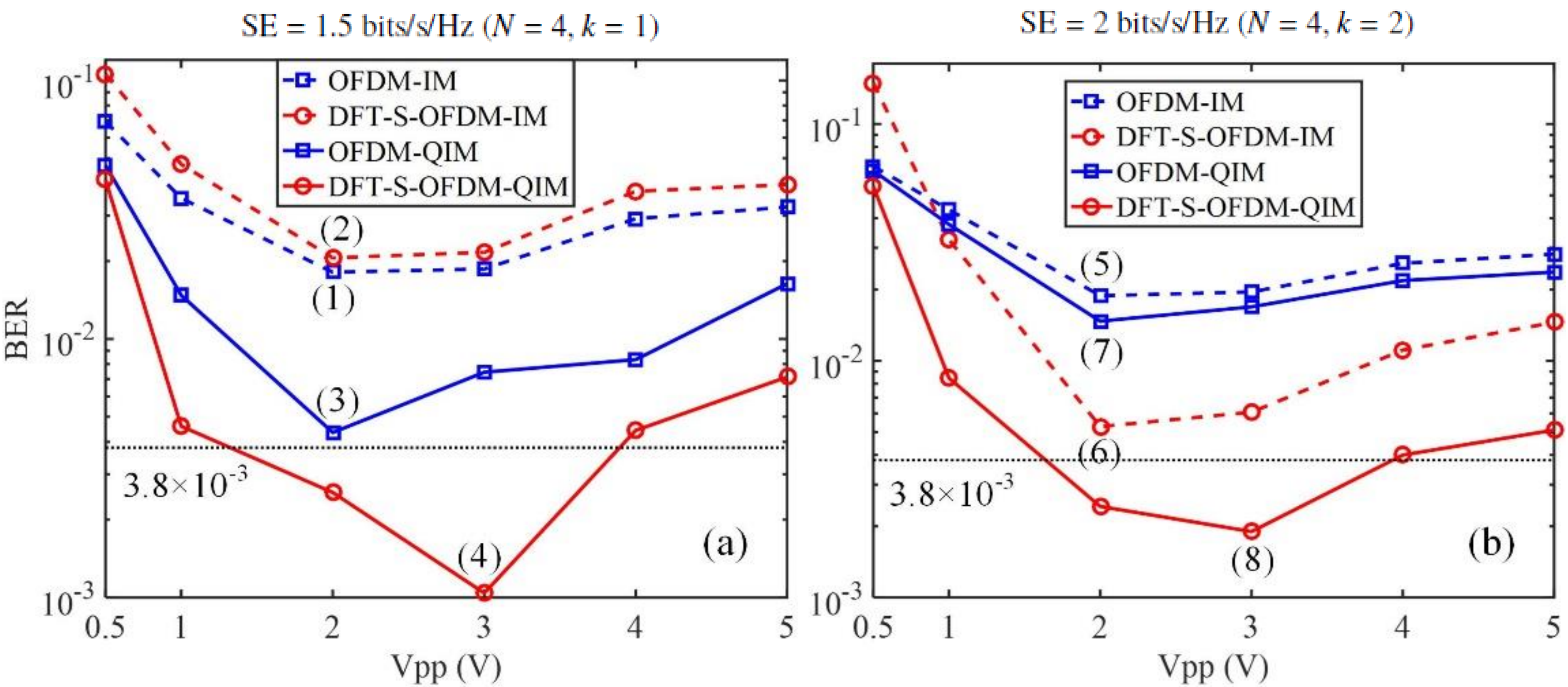
Simulation results:



- **DFT spreading cannot reduce PAPR for OFDM-IN when *k* = 1**
- **DFT-S-OFDM-QIM achieves much lower PAPR than DFT-S-OFDM-IM**

F. Ahmed, Y. G. Nie, **C. Chen***, et al., "DFT-spread OFDM with quadrature index modulation for practical VLC systems," Optics Express, 2021.

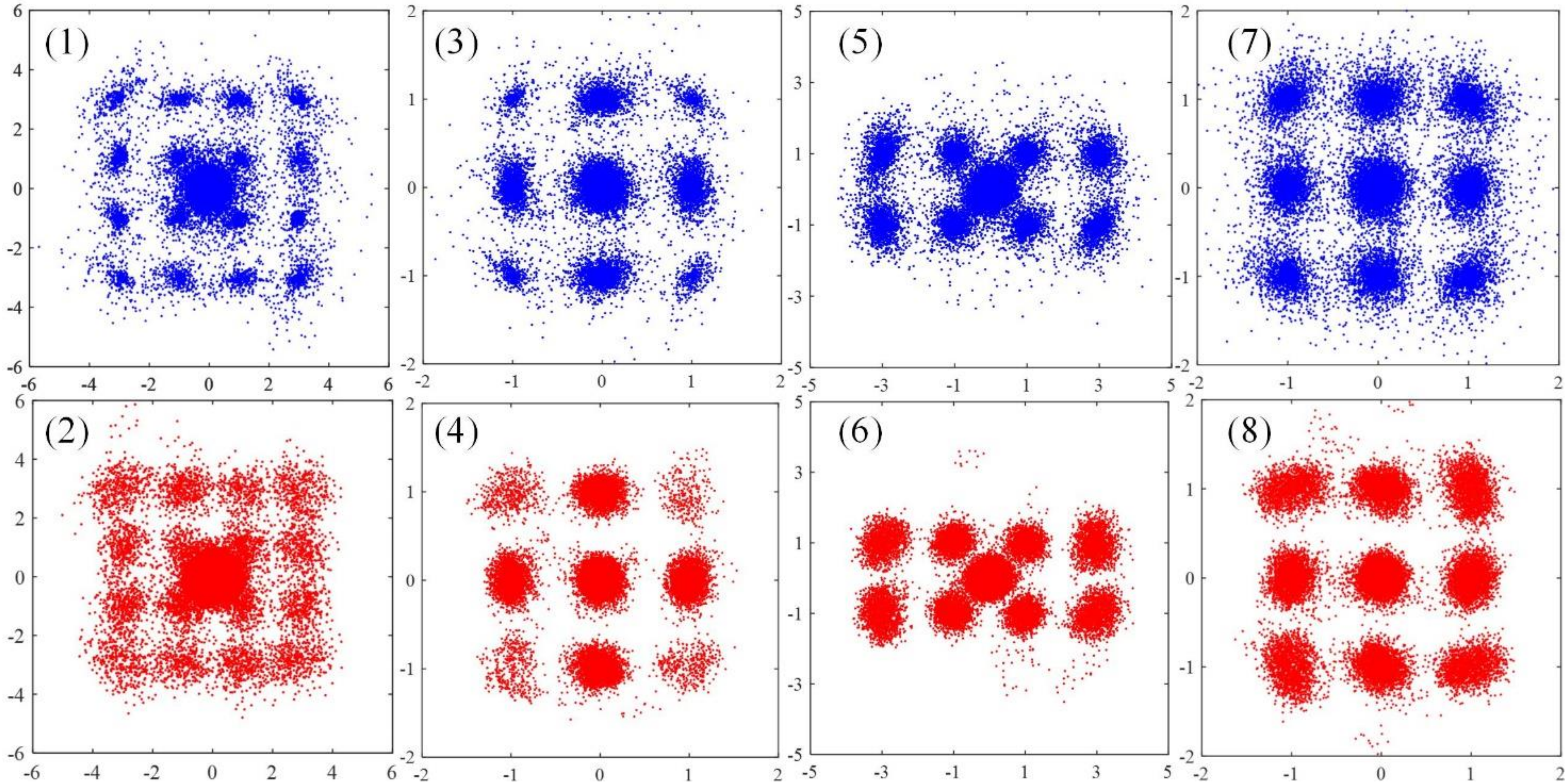
Experimental results:



- **DFT-S-OFDM-QIM always achieves the best BER performance**
- **DFT-S-OFDM-QIM can use a large Vpp, due to its lowest PAPR**

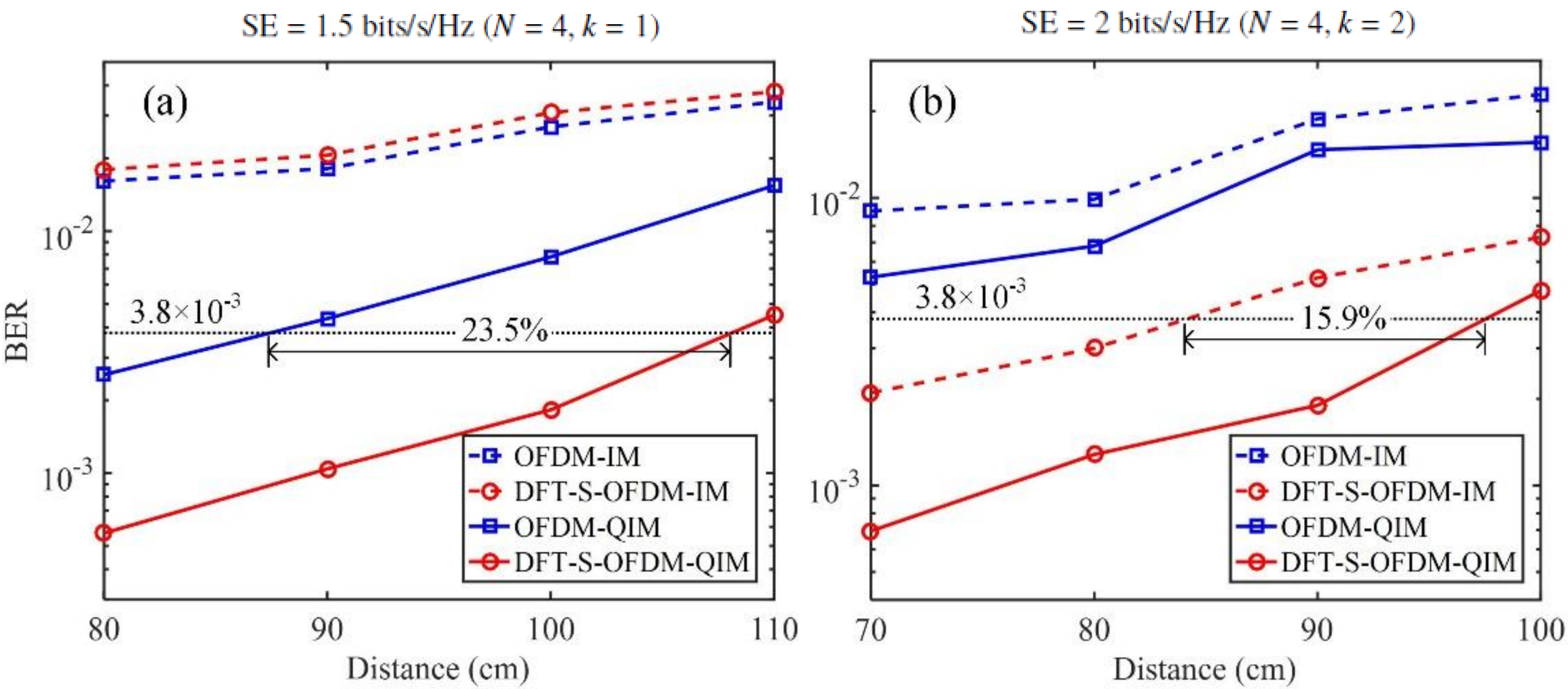
F. Ahmed, Y. G. Nie, **C. Chen***, et al., "DFT-spread OFDM with quadrature index modulation for practical VLC systems," Optics Express, 2021.

Experimental results:



F. Ahmed, Y. G. Nie, **C. Chen***, et al., "DFT-spread OFDM with quadrature index modulation for practical VLC systems," Optics Express, 2021.

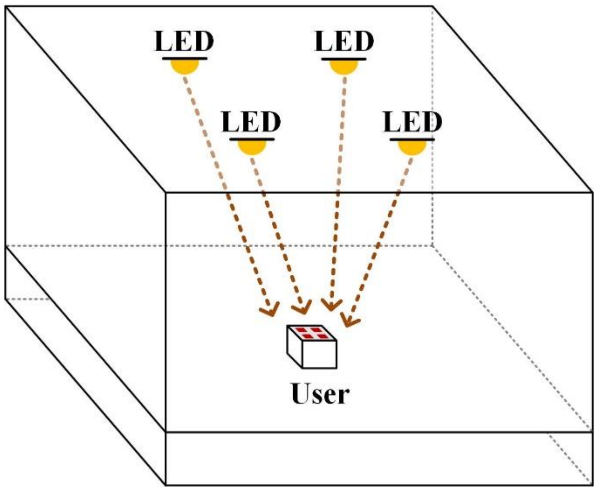
Experimental results:



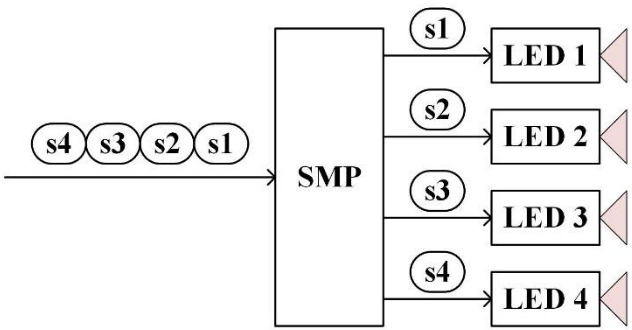
- **DFT-S-OFDM-QIM always achieves the largest transmission distance**
- **A larger distance extension is obtained for a smaller *k***

F. Ahmed, Y. G. Nie, **C. Chen***, et al., “DFT-spread OFDM with quadrature index modulation for practical VLC systems,” Optics Express, 2021.

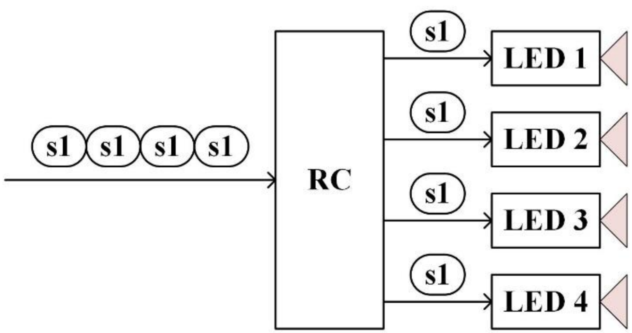
MIMO传输的三种模式



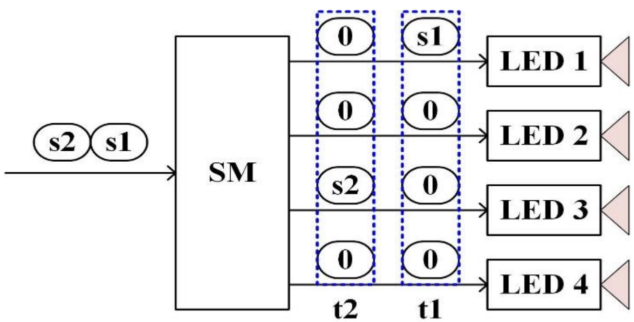
Spatial Multiplexing (SMP)



Repetition Coding (RC)

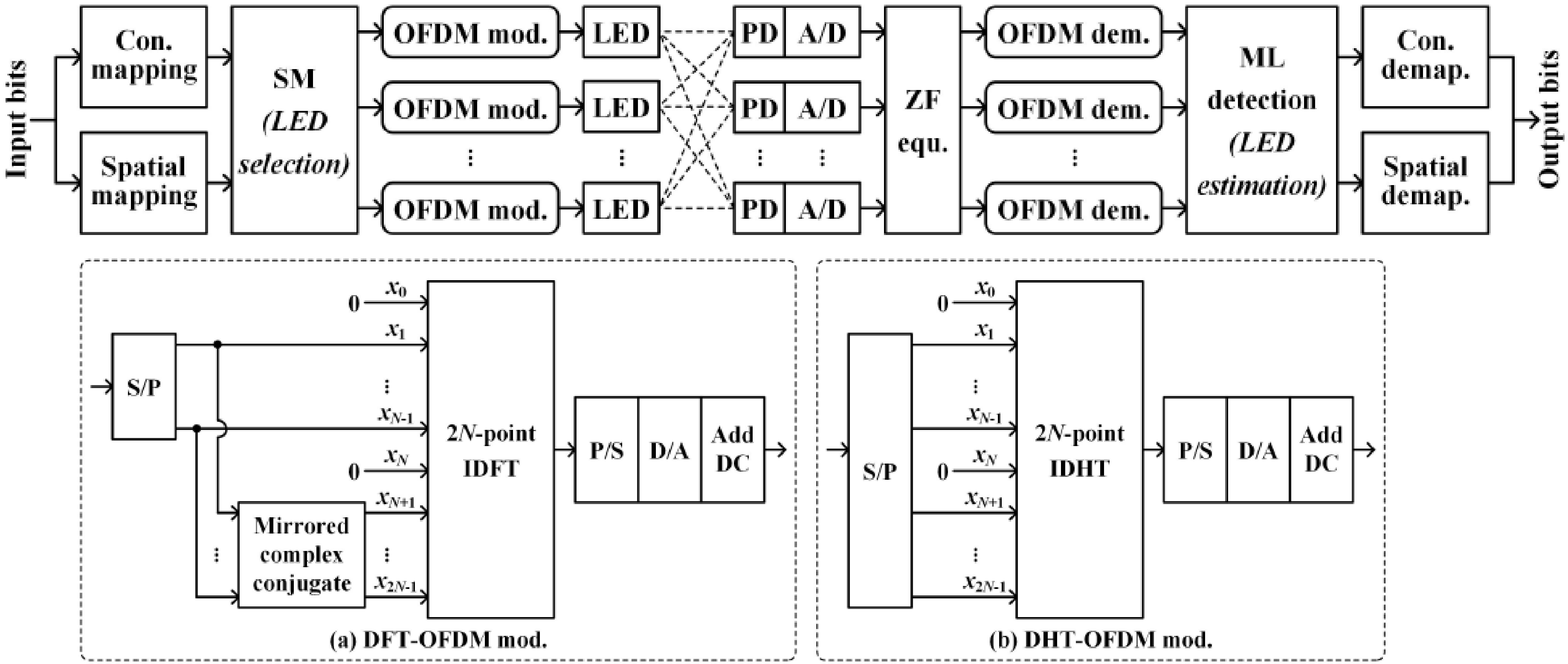


Spatial Modulation (SM)



T. Fath and H. Haas, "Performance comparison of MIMO techniques for optical wireless communications in indoor environments," IEEE Trans. Commun., pp. 733–742, Feb. 2013.

相关成果：（1） DHT-OFDM-based SM



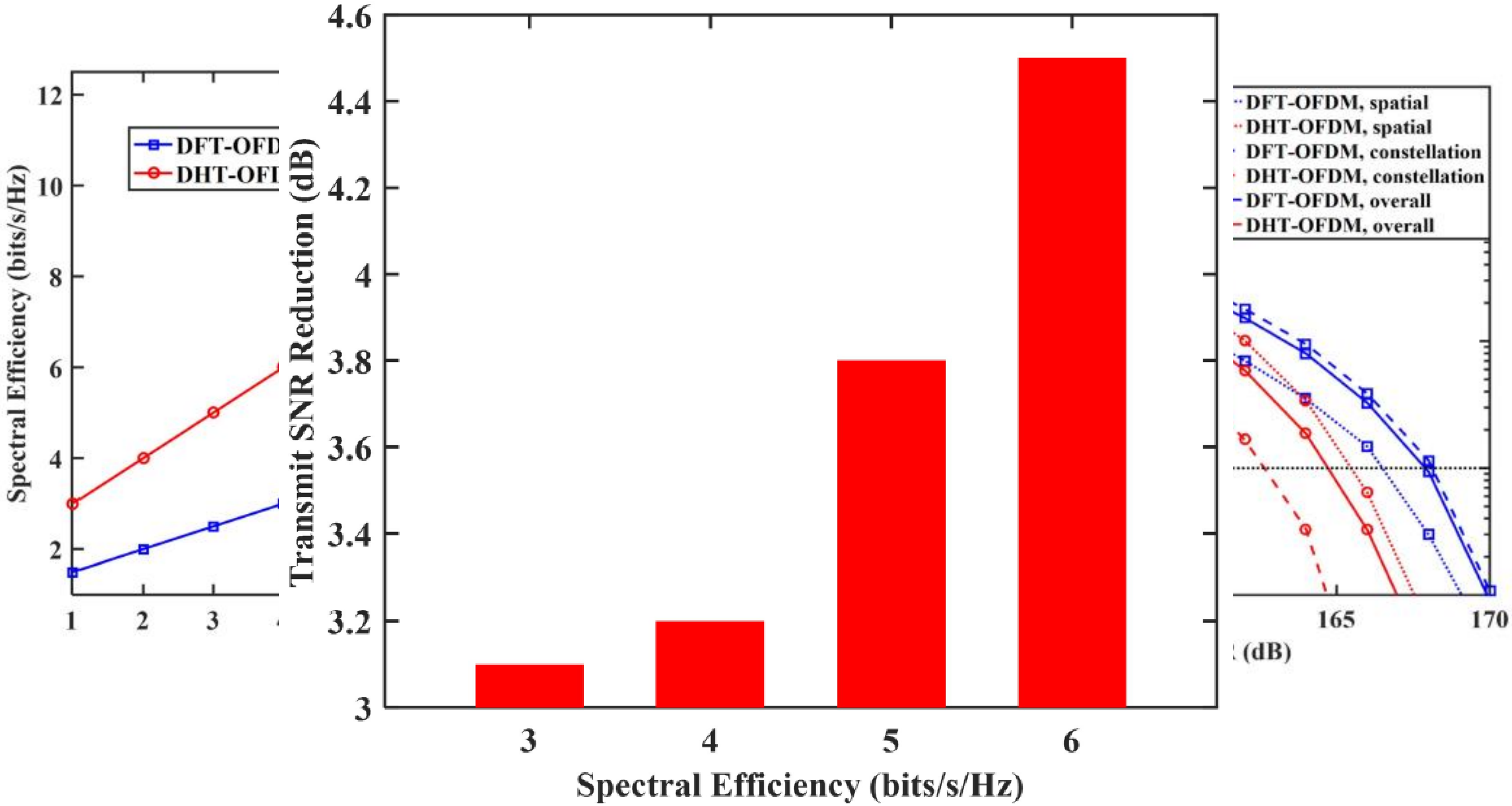
Self-inverse: DHT and IDHT are the same

- IDHT/DHT + 1D constellation (i.e., PAM)
- Hermitian symmetry constraint is not required
- LED selection can only be performed with respect to all the subcarriers

C. Chen, et al., "DHT-OFDM based spatial modulation for optical wireless communication," IEEE OGC, 2020. (Best Paper Award)

VLC物理层MIMO传输技术

相关成果：（1） DHT-OFDM-based SM

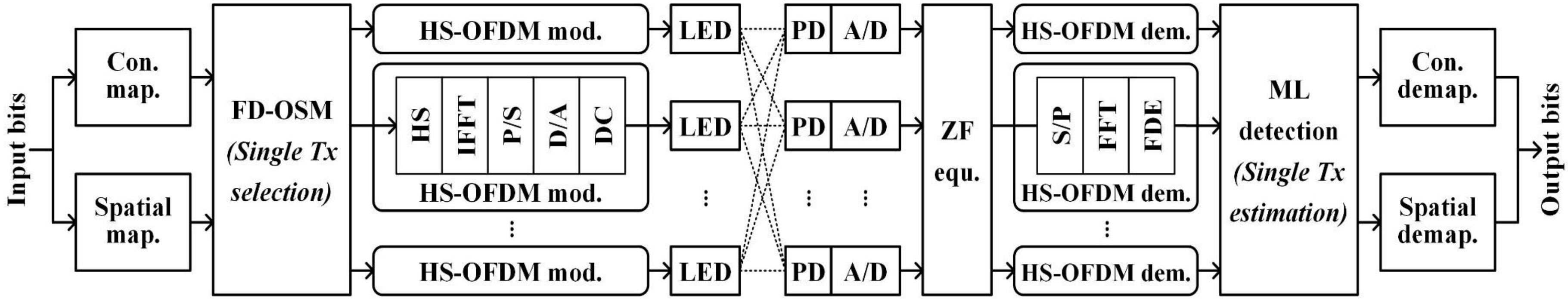


A larger SNR gain is achieved for a higher SE

C. Chen, et al., "DHT-OFDM based spatial modulation for optical wireless communication," IEEE OGC, 2020. (Best Paper Award)

相关成果：（2） Enhanced OFDM-based SM

Principle of FD-OSM using HS-OFDM:



Spectral efficiency with M-QAM constellation and N_t LED transmitters:

$$\eta_{\text{FD-OSM}} = \underbrace{\frac{1}{2}\log_2(M)}_{\text{constellation}} + \underbrace{\frac{1}{2}\lfloor\log_2(N_t)\rfloor}_{\text{spatial}},$$

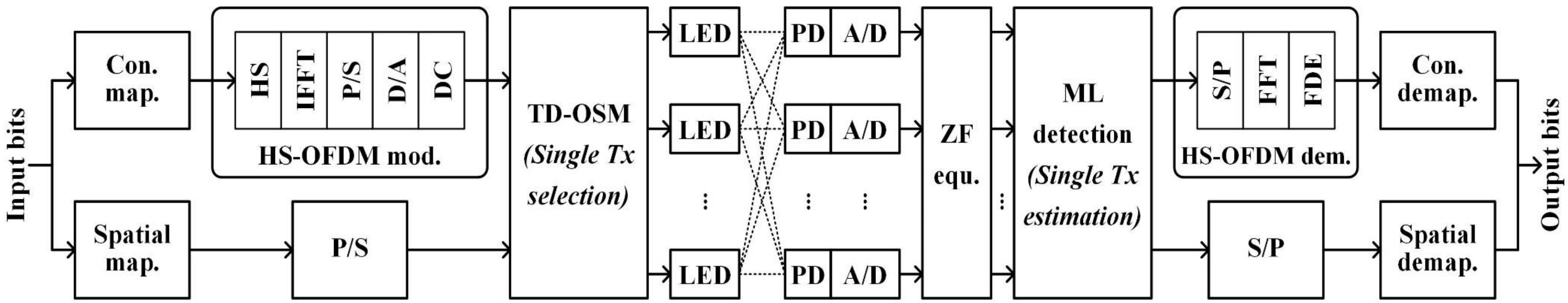
Hermitian symmetry (HS) constraint！

- FD-OSM mapping (HS-OFDM mod. selection) in the frequency domain, i.e., subcarrier level

C. Chen, et al., "Enhanced OFDM-based optical spatial modulation," IEEE International Conference on Communications (ICC), 2021.

相关成果：（2） Enhanced OFDM-based SM

Principle of TD-OSM using HS-OFDM:



Spectral efficiency with *M*-QAM constellation and N_t LED transmitters:

$$\eta_{\text{TD-OSM}} = \underbrace{\frac{1}{2}\log_2(M)}_{\text{constellation}} + \underbrace{\lfloor \log_2(N_t) \rfloor}_{\text{spatial}}.$$

Doubled spatial bits !

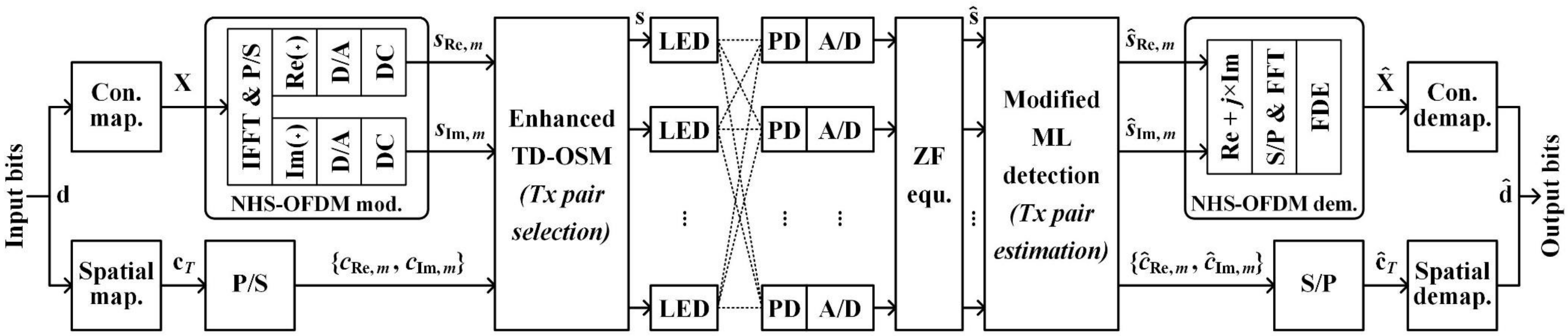
HS constraint !

- TD-OSM mapping (LED selection) in the time domain
- Need a secondary DC bias to avoid the loss of spatial information

C. Chen, et al., "Enhanced OFDM-based optical spatial modulation," IEEE International Conference on Communications (ICC), 2021.

相关成果：（2） Enhanced OFDM-based SM

Principle of our proposed enhanced scheme: TD-OSM using NHS-OFDM (eTD-OSM)



Spectral efficiency with *M*-QAM constellation and N_t LED transmitters:

$$\eta_{\mathrm{eTD-SM}} = \underbrace{\log_2(M)}_{\text{constellation}} + \underbrace{\lfloor \log_2(C(N_t,2)) \rfloor}_{\text{spatial}}.$$

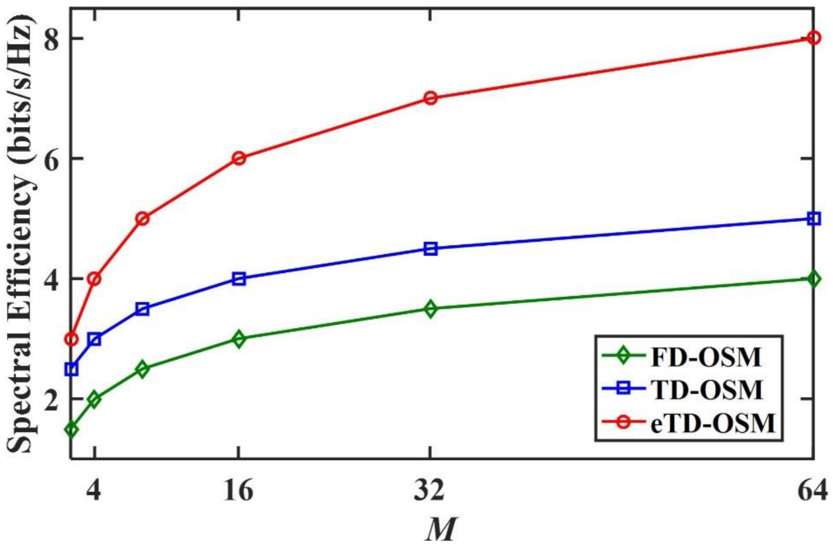
More selections, more spatial bits !

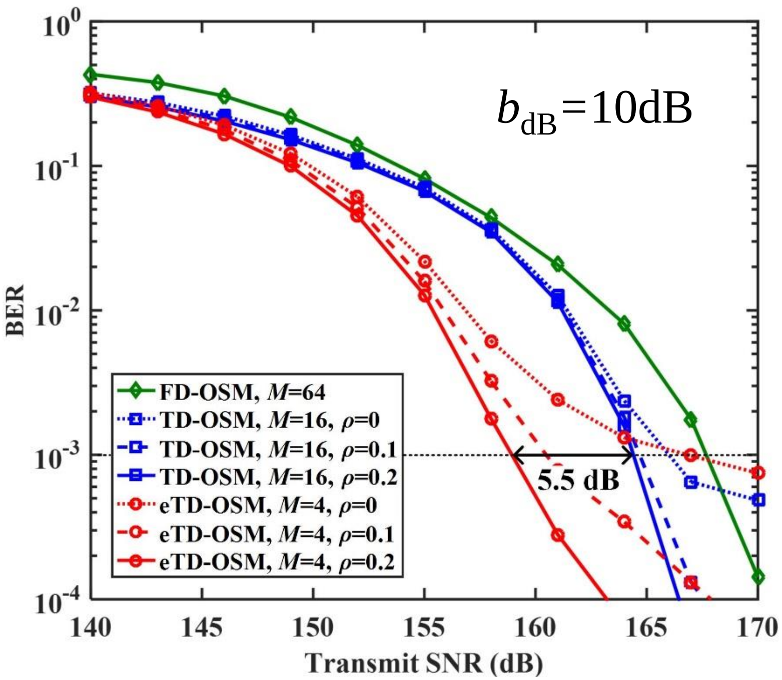
No HS constraint, doubled constellation bits !

◆ eTD-OSM mapping (LED pair selection) in the time domain

C. Chen, et al., "Enhanced OFDM-based optical spatial modulation," IEEE International Conference on Communications (ICC), 2021.

相关成果：（2） Enhanced OFDM-based SM



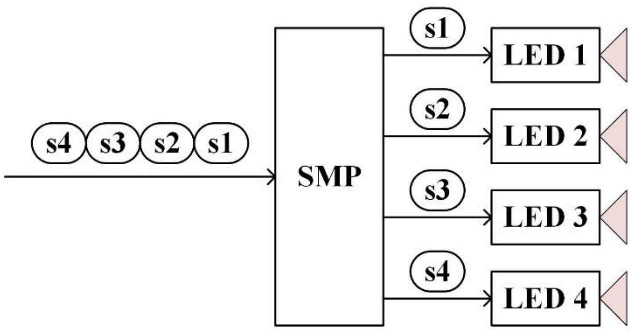


Substantially higher SE for large constellations, 5.5-dB SNR gain

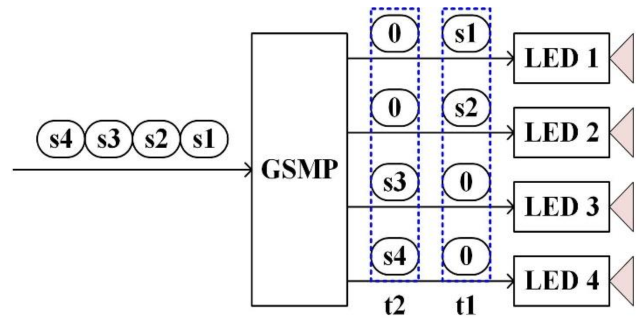
C. Chen, et al., "Enhanced OFDM-based optical spatial modulation," IEEE International Conference on Communications (ICC), 2021.

相关成果： （3） OFDM-based generalized optical MIMO (GOMIMO)

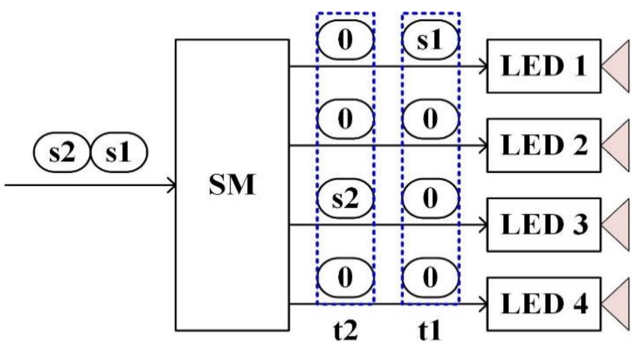
Spatial Multiplexing (SMP)



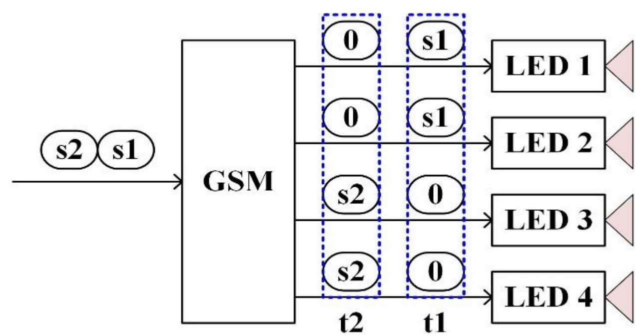
GSMP



Spatial Modulation (SM)



GSM



C. Chen, et al., “OFDM-based generalized optical MIMO,” Journal of Lightwave Technology, 2021

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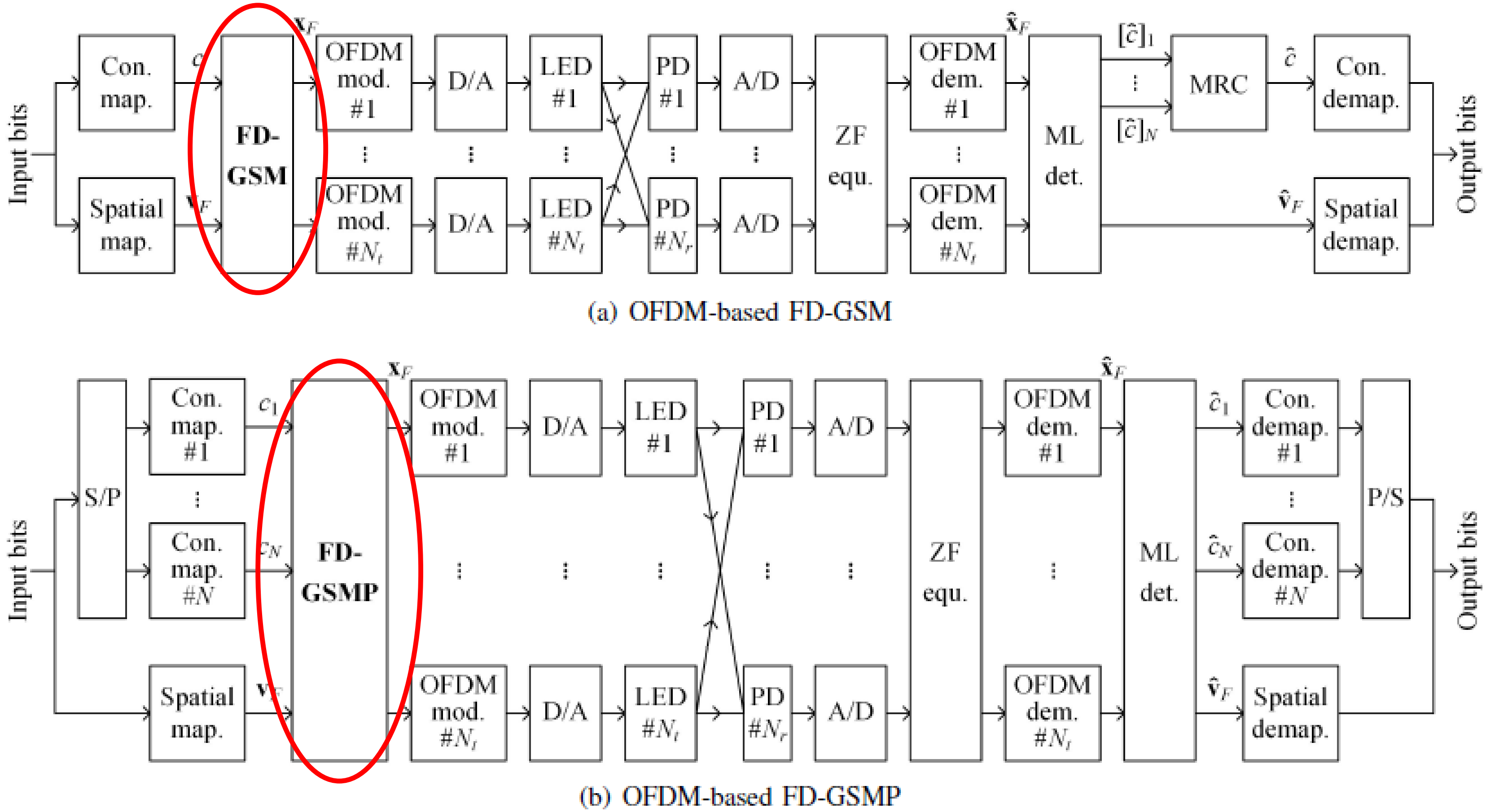
相关成果：（3） OFDM-based generalized optical MIMO (GOMIMO)

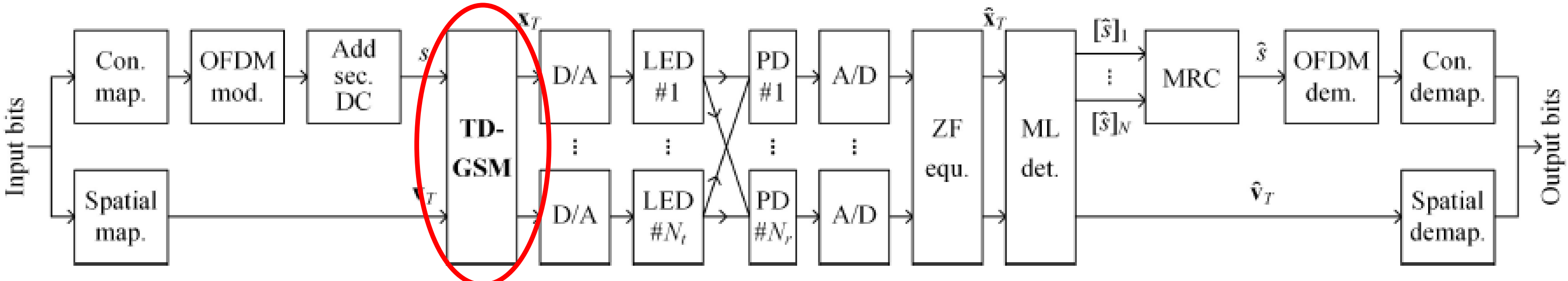
Principle of OFDM-based FD-GSM and FD-GSMP:



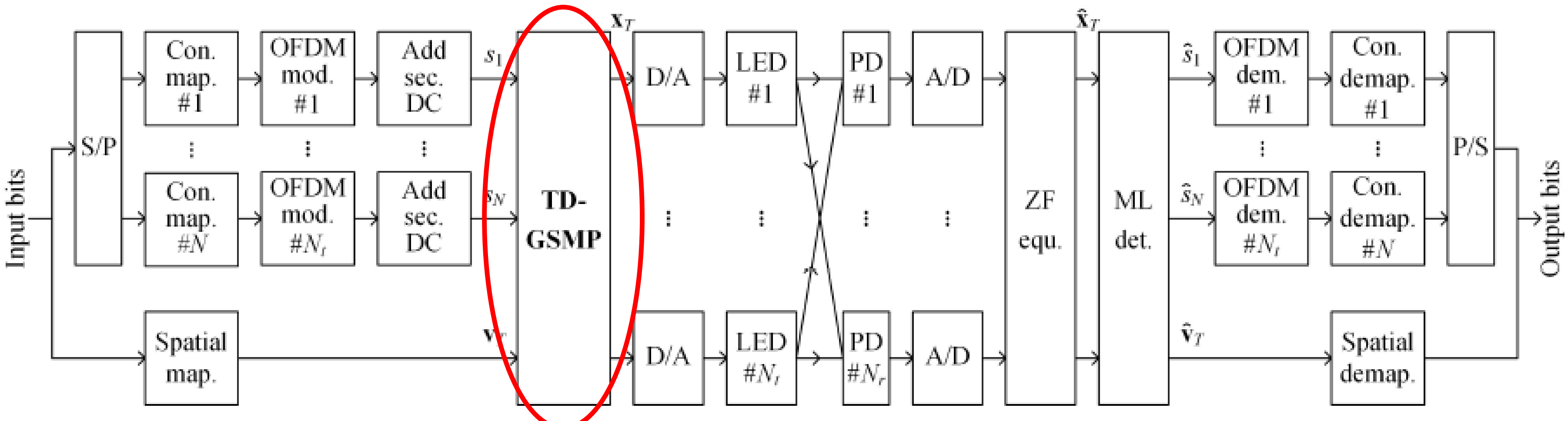
C. Chen, et al., "OFDM-based generalized optical MIMO," Journal of Lightwave Technology, 2021

相关成果：（3） OFDM-based generalized optical MIMO (GOMIMO)

Principle of OFDM-based TD-GSM and TD-GSMP:



(a) OFDM-based TD-GSM

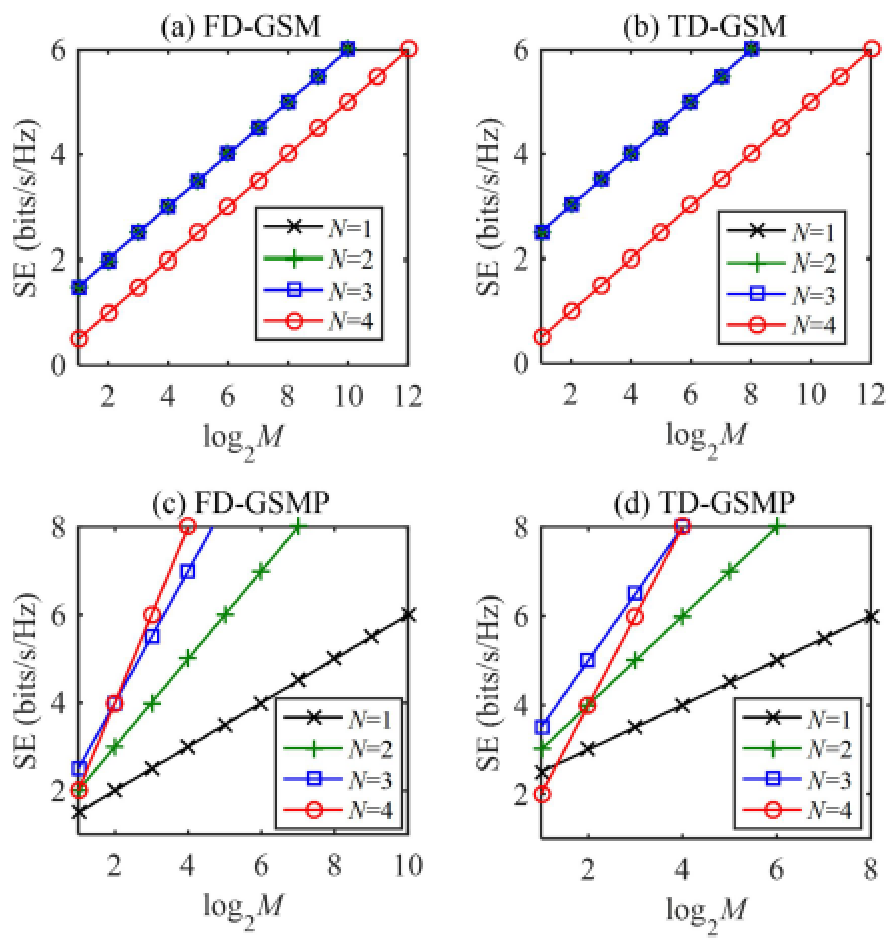


(b) OFDM-based TD-GSMP

C. Chen, et al., "OFDM-based generalized optical MIMO," Journal of Lightwave Technology, 2021

相关成果：（3） OFDM-based generalized optical MIMO (GOMIMO)

4×4 MIMO with *N* activated LEDs:



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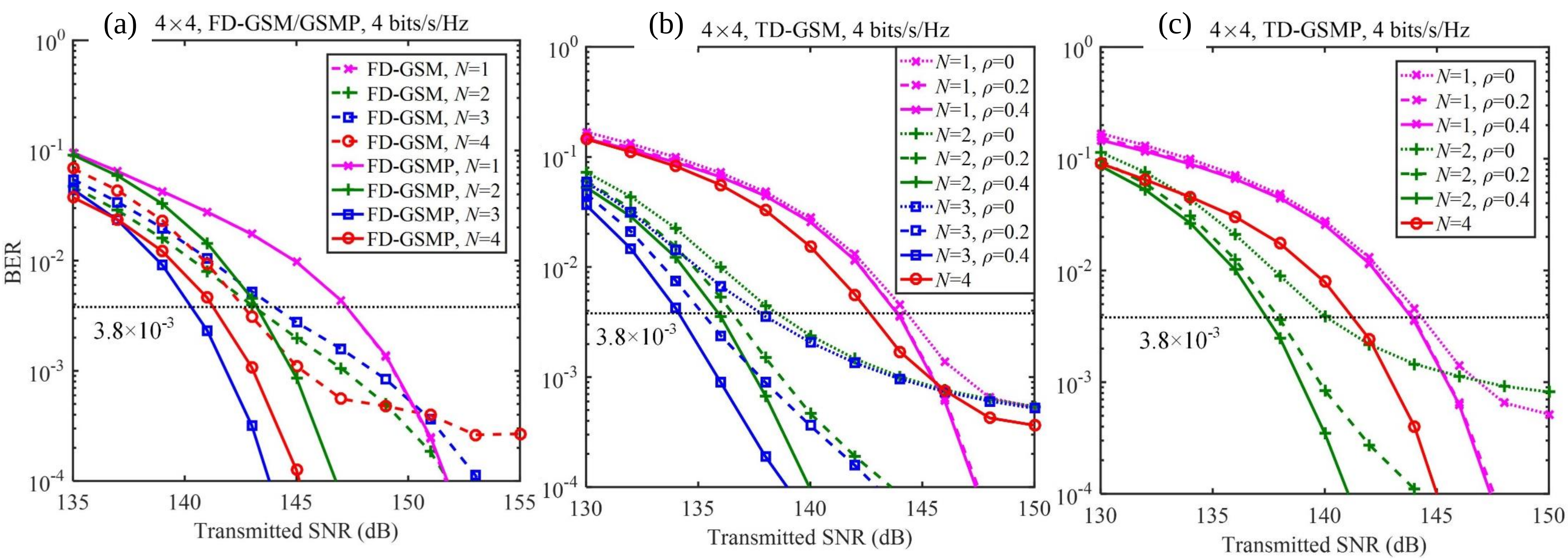
相关成果： （3） OFDM-based generalized optical MIMO (GOMIMO)

4×4 MIMO with *N* activated LEDs:



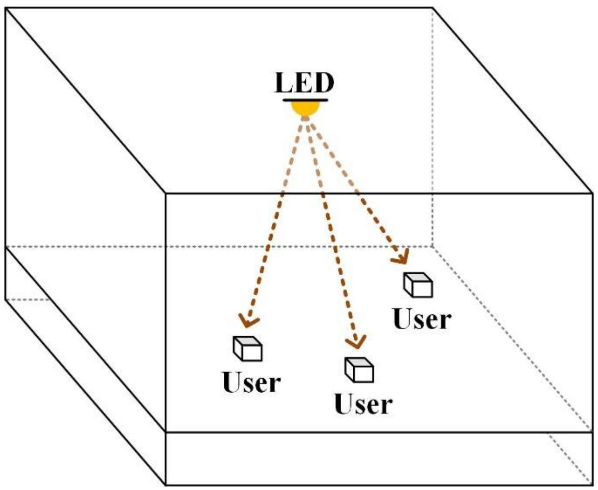
Scenario	Optimal technique	Minimum SNR
3 bits/s/Hz	TD-GSM, $N = 3$, $\rho = 0.4$	133.1 dB
4 bits/s/Hz	TD-GSM, $N = 3$, $\rho = 0.4$	134.1 dB
5 bits/s/Hz	TD-GSMP, $N = 3$, $\rho = 0.4$	138.7 dB

User-centric design for different SEs and user positions

C. Chen, et al., “OFDM-based generalized optical MIMO,” Journal of Lightwave Technology, 2021

VLC物理层多用户接入技术

常见用户多址接入方案



- Precoding to remove multi-user interference

  Challenging due to limited dynamic range and severe nonlinearity of LED

- Conventional OFDMA

  Reduced user bandwidth due to spectrum partitioning

- NOMA using SPC/SIC

  Error propagation due to imperfect SIC

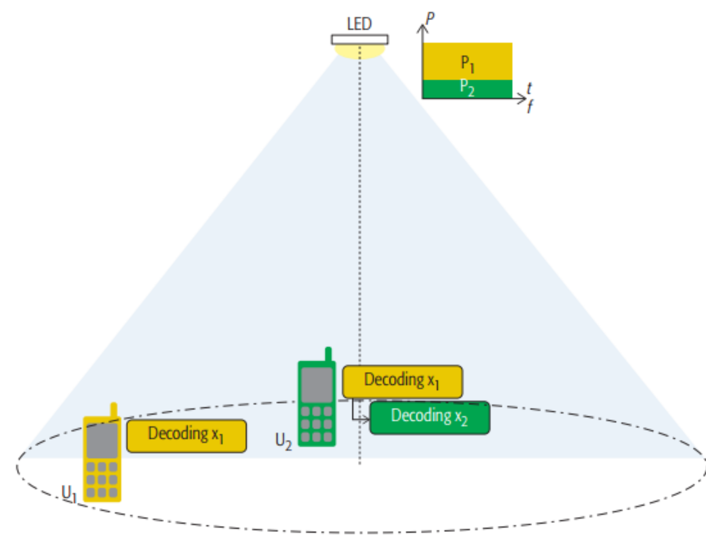
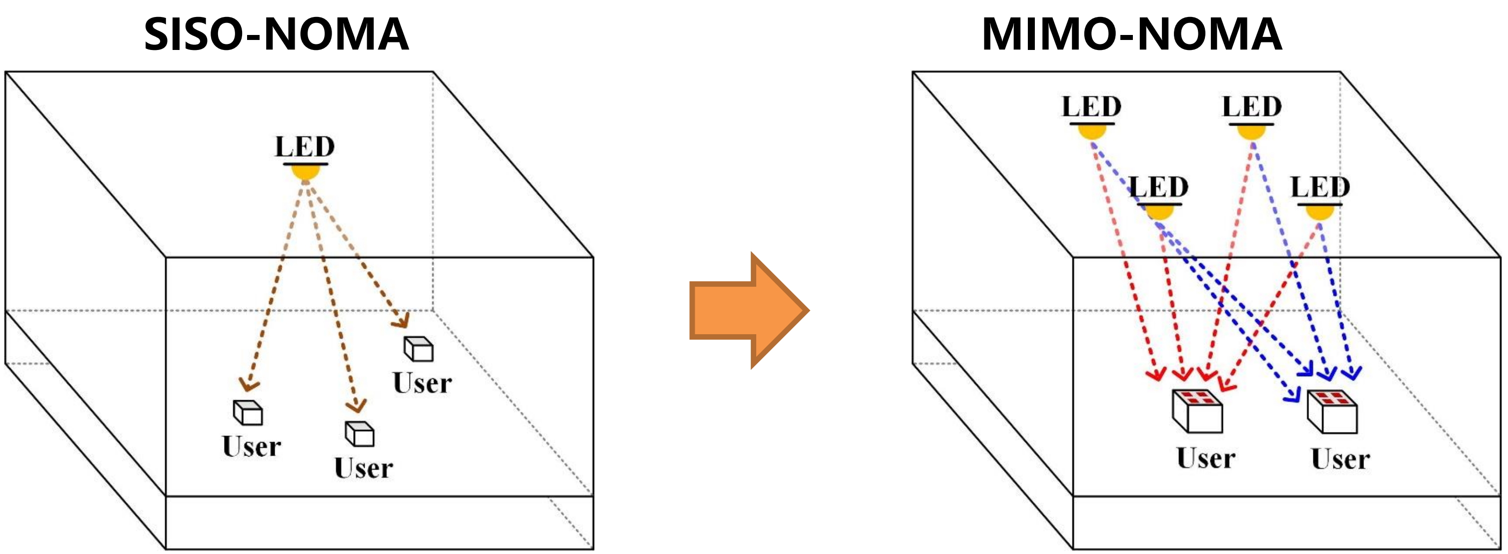


Illustration of downlink NOMA-VLC

相关成果： （1）MIMO-NOMA-based VLC



- Sum channel gain-based user sorting

$$h_{1i,1} + h_{2i,1} > h_{1i,2} + h_{2i,2} > \cdots > h_{1i,K} + h_{2i,K}$$
$$\mathrm{O}_{i,1} < \mathrm{O}_{i,2} < \cdots < \mathrm{O}_{i,K}$$

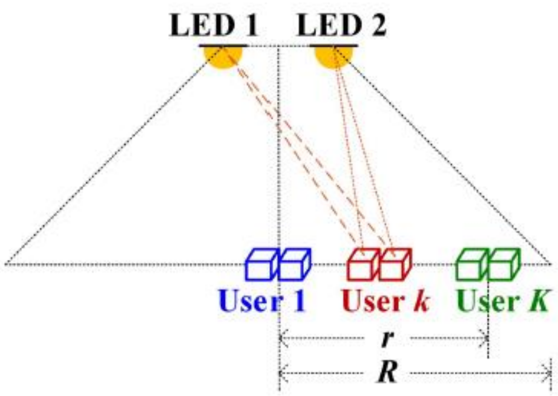
- Normalized gain difference power allocation (NGDPA)

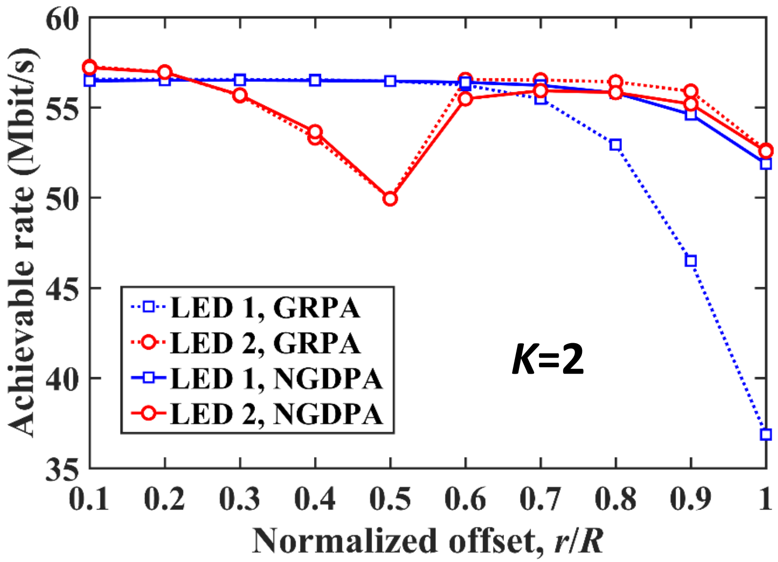
$$\rho_{i,k} = \left(\frac{h_{1i,1} + h_{2i,1} - h_{1i,k+1} - h_{2i,k+1}}{h_{1i,1} + h_{2i,1}} \right)^k \rho_{i,k+1}$$

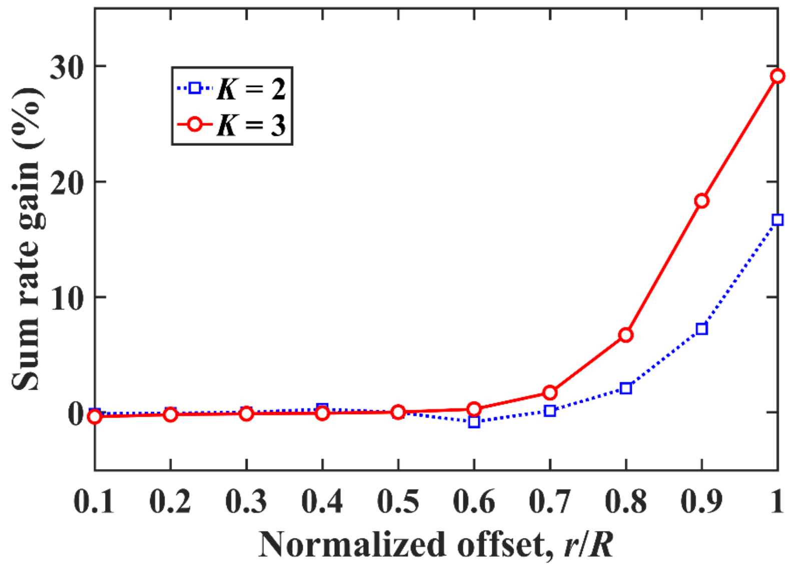
C. Chen, et al., "On the performance of MIMO-NOMA-based visible light communication systems," IEEE Photonics Technology Letters, 2018.

相关成果：（1）MIMO-NOMA-based VLC

2×2 MIMO:





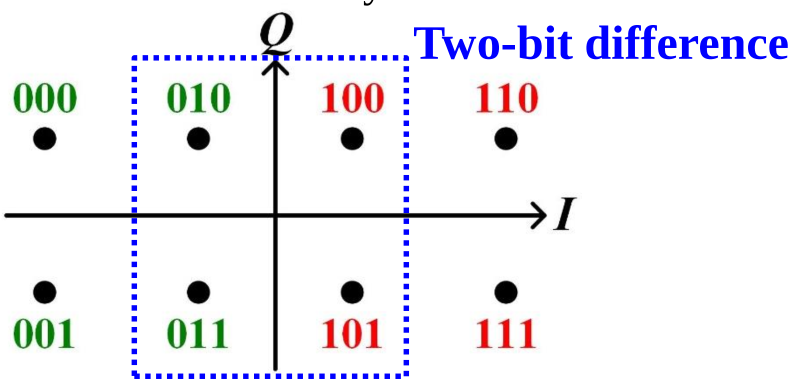


A larger sum rate gain for *K*=3 with more distinctive channel conditions

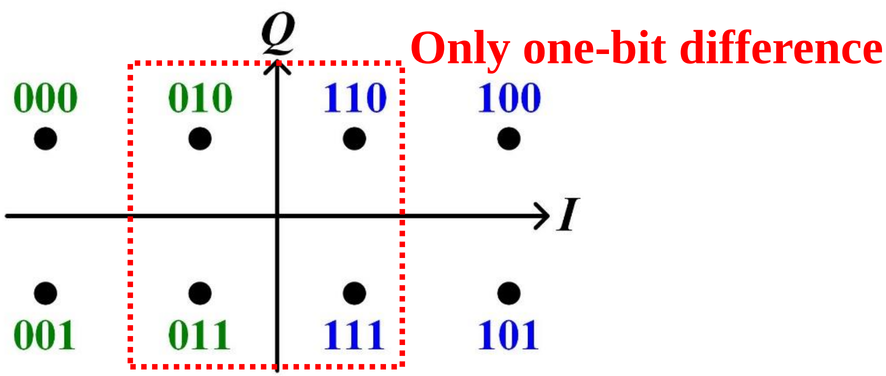
C. Chen, et al., "On the performance of MIMO-NOMA-based visible light communication systems," IEEE Photonics Technology Letters, 2018.

相关成果：（2）SIC-free NOMA based on CPC/UCD

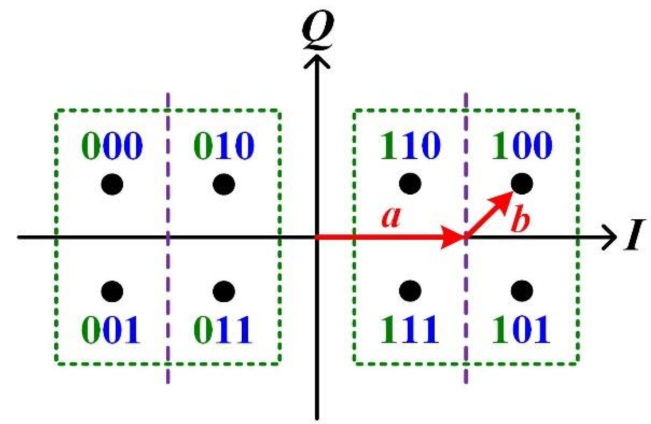
Non-Gray-coded 8-QAM constellation by SPC



Gray-coded 8-QAM constellation for CPC

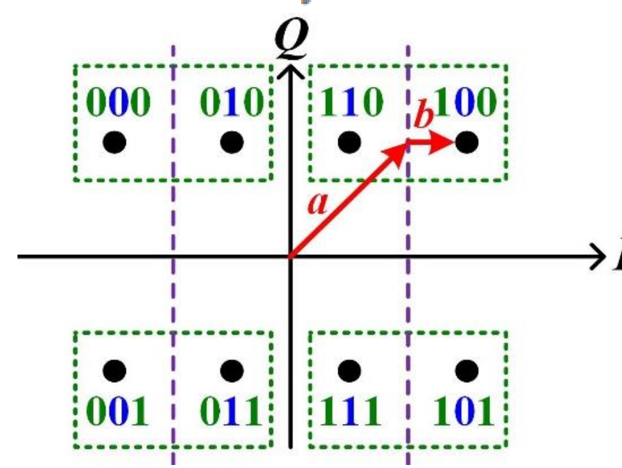


$b_n = b_2 b_3,\ b_f = b_1$



$$\rho = \frac{a^2}{b^2}$$

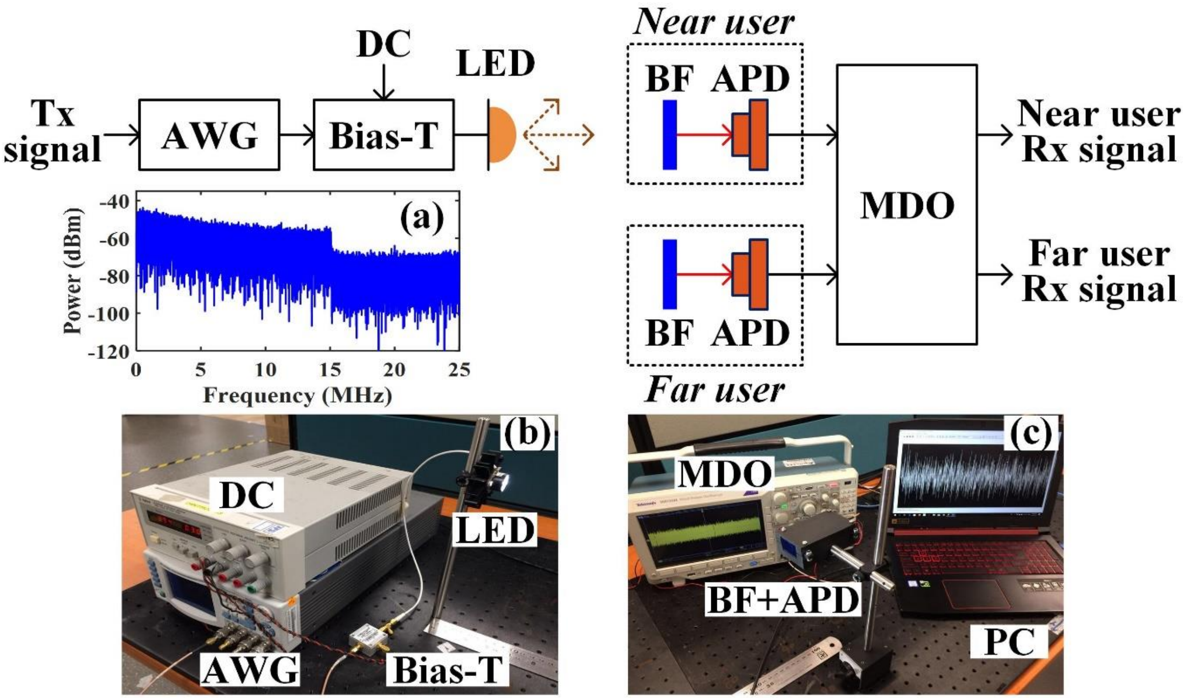
$b_n = b_2,\ b_f = b_1 b_3$



C. Chen, et al., “Flexible-rate SIC-free NOMA for downlink VLC based on constellation partitioning coding,” IEEE WCL, 2019.

相关成果：（2）SIC-free NOMA based on CPC/UCD

Two-user experiments with 45 Mbit/s over 100 cm:

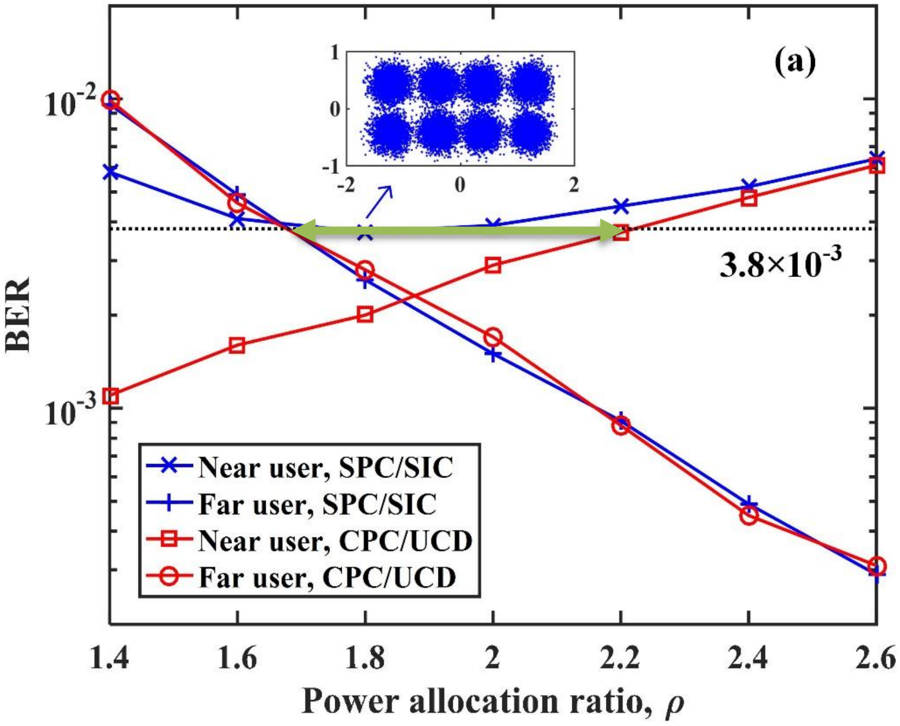


Experimental setup of the two-user VLC system

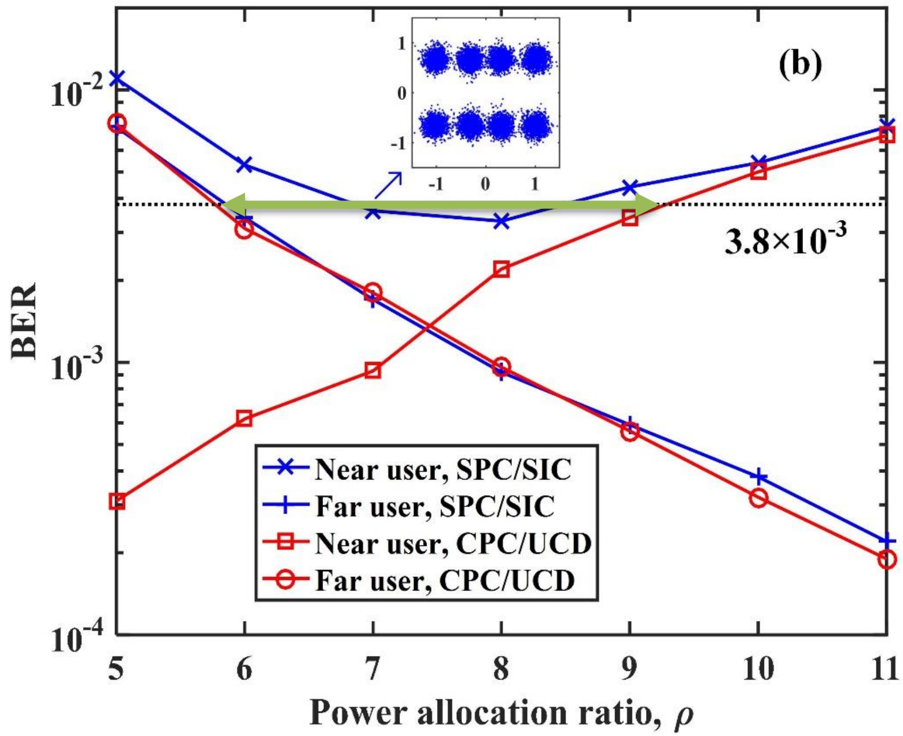
C. Chen, et al., "Flexible-rate SIC-free NOMA for downlink VLC based on constellation partitioning coding," IEEE WCL, 2019.

相关成果：（2）SIC-free NOMA based on CPC/UCD

Two-user experiments with 45 Mbit/s over 100 cm:



$b_n = b_2 b_3, b_f = b_1$



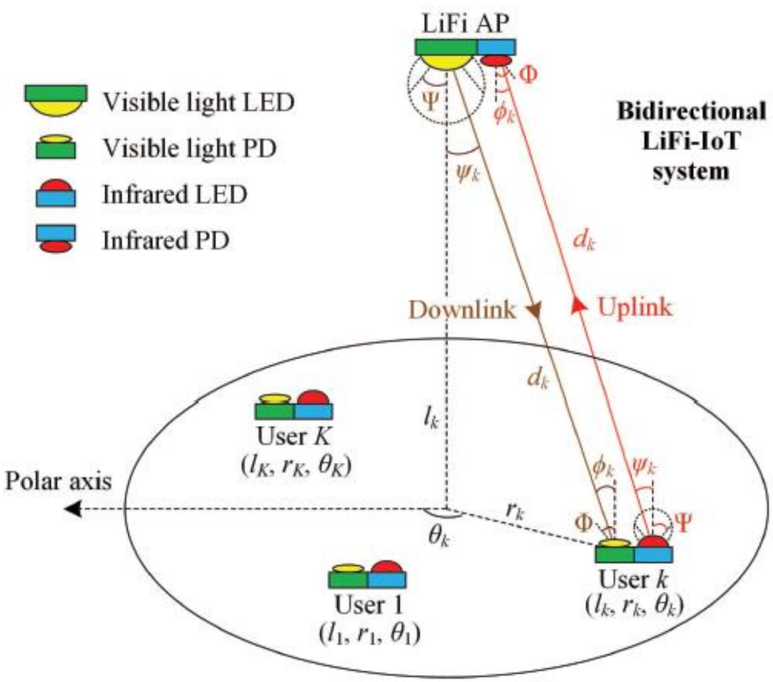
$b_n = b_2, b_f = b_1 b_3$

Effective power allocation ratio range can be substantially extended

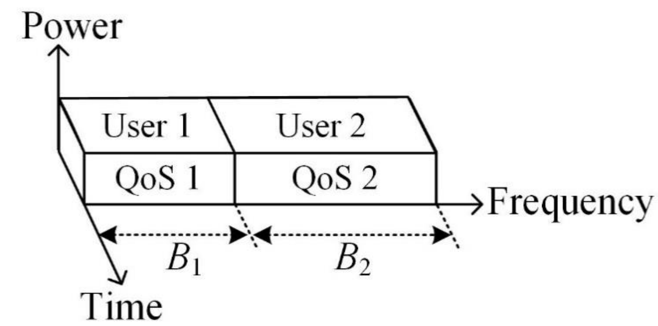
C. Chen, et al., “Flexible-rate SIC-free NOMA for downlink VLC based on constellation partitioning coding,” IEEE WCL, 2019.

VLC物理层多用户接入技术

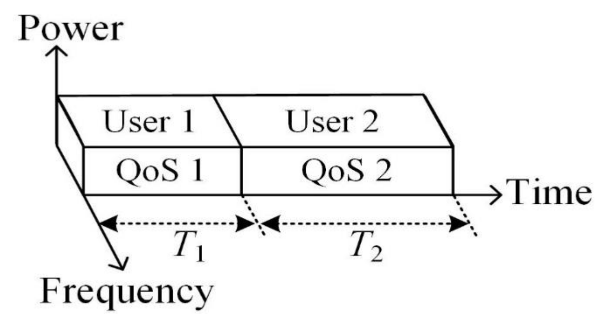
相关成果：（3） Energy-efficient NOMA for LiFi-IoT



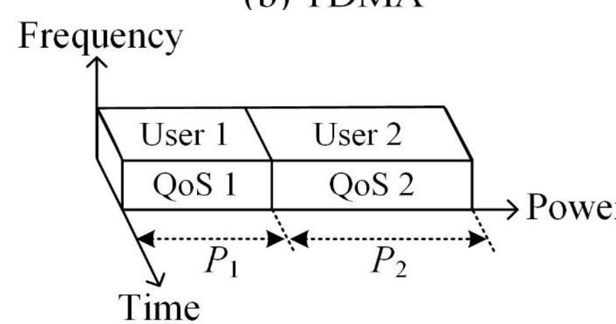
- Energy Consumption
- Diverse Device QoS Requirements



(a) FDMA/OFDMA



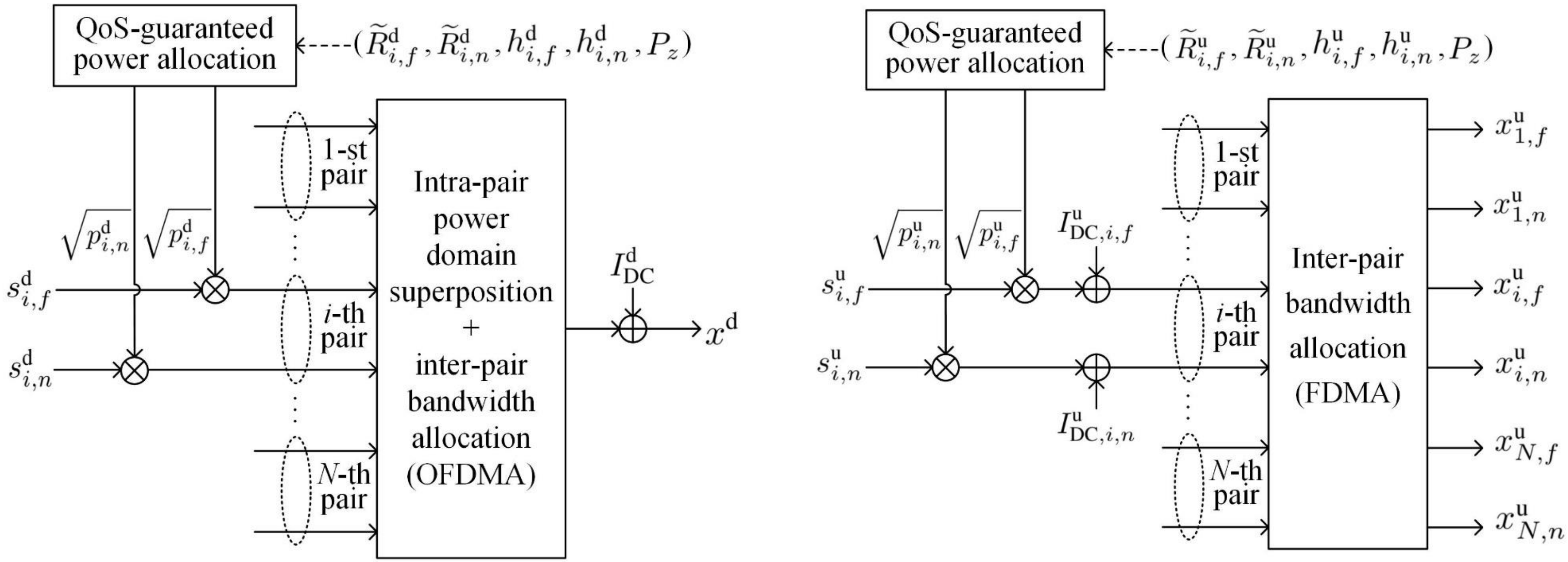
(b) TDMA



(c) NOMA

C. Chen, et al., "NOMA for energy-efficient LiFi-enabled bidirectional IoT communication," IEEE Transactions on Communications, 2021.

相关成果：（3） Energy-efficient NOMA for LiFi-IoT



(a) Downlink (b) Uplink

Downlink power requirements:

$$\begin{cases} p^{\mathrm{d}}_{i,\mathrm{high}} \geq \mathbb{R}^{\mathrm{d}}_{i,\mathrm{high}} \left(\mathbb{R}^{\mathrm{d}}_{i,\mathrm{low}} \frac{P_z}{(h^{\mathrm{d}}_{i,\mathrm{low}})^2} + \frac{P_z}{(h^{\mathrm{d}}_{i,\mathrm{min}})^2} \right) \\ p^{\mathrm{d}}_{i,\mathrm{low}} \geq \mathbb{R}^{\mathrm{d}}_{i,\mathrm{low}} \frac{P_z}{(h^{\mathrm{d}}_{i,\mathrm{low}})^2} \end{cases}$$

Uplink power requirements:

$$\begin{cases} p^{\mathrm{u}}_{i,\mathrm{high}} \geq \mathbb{R}^{\mathrm{u}}_{i,\mathrm{high}} (\mathbb{R}^{\mathrm{u}}_{i,\mathrm{low}} + 1) \frac{P_z}{(h^{\mathrm{u}}_{i,\mathrm{high}})^2} \\ p^{\mathrm{u}}_{i,\mathrm{low}} \geq \mathbb{R}^{\mathrm{u}}_{i,\mathrm{low}} \frac{P_z}{(h^{\mathrm{u}}_{i,\mathrm{low}})^2} \end{cases}$$

C. Chen, et al., “NOMA for energy-efficient LiFi-enabled bidirectional IoT communication,” IEEE Transactions on Communications, 2021.

相关成果：（3） Energy-efficient NOMA for LiFi-IoT

Optimal decoding order:

Proposition 1: The optimal decoding orders for the far and near users in the i-th user pair in the downlink and uplink channels of the bidirectional LiFi-IoT system are given by $\mathbb{O}^{\mathrm{d}}_{i,f} \geq \mathbb{O}^{\mathrm{d}}_{i,n}$ and $\mathbb{O}^{\mathrm{u}}_{i,f} < \mathbb{O}^{\mathrm{u}}_{i,n}$, respectively.

QoS-guaranteed optimal power allocation:

$$\begin{cases} p^{\mathrm{d}}_{i,f} \geq \mathbb{R}^{\mathrm{d}}_{i,f}\left(\mathbb{R}^{\mathrm{d}}_{i,n}\frac{P_z}{(h^{\mathrm{d}}_{i,n})^2} + \frac{P_z}{(h^{\mathrm{d}}_{i,f})^2}\right) \\ p^{\mathrm{d}}_{i,n} \geq \mathbb{R}^{\mathrm{d}}_{i,n}\frac{P_z}{(h^{\mathrm{d}}_{i,n})^2} \end{cases}$$

$$\begin{cases} p^{\mathrm{u}}_{i,f} \geq \mathbb{R}^{\mathrm{u}}_{i,f}\frac{P_z}{(h^{\mathrm{u}}_{i,f})^2} \\ p^{\mathrm{u}}_{i,n} \geq \mathbb{R}^{\mathrm{u}}_{i,n}(\mathbb{R}^{\mathrm{u}}_{i,f}+1)\frac{P_z}{(h^{\mathrm{u}}_{i,n})^2} \end{cases}$$

EE

$$\eta^b = \frac{R^b}{P^b_{\mathrm{elec}}}$$

max EE

$$\begin{cases} p^{\mathrm{d,OPA}}_{i,f} = \mathbb{R}^{\mathrm{d}}_{i,f}\left(\mathbb{R}^{\mathrm{d}}_{i,n}\frac{P_z}{(h^{\mathrm{d}}_{i,n})^2} + \frac{P_z}{(h^{\mathrm{d}}_{i,f})^2}\right) \\ p^{\mathrm{d,OPA}}_{i,n} = \mathbb{R}^{\mathrm{d}}_{i,n}\frac{P_z}{(h^{\mathrm{d}}_{i,n})^2} \end{cases}$$

$$\begin{cases} p^{\mathrm{u,OPA}}_{i,f} = \mathbb{R}^{\mathrm{u}}_{i,f}\frac{P_z}{(h^{\mathrm{u}}_{i,f})^2} \\ p^{\mathrm{u,OPA}}_{i,n} = \mathbb{R}^{\mathrm{u}}_{i,n}(\mathbb{R}^{\mathrm{u}}_{i,f}+1)\frac{P_z}{(h^{\mathrm{u}}_{i,n})^2} \end{cases}$$

C. Chen, et al., “NOMA for energy-efficient LiFi-enabled bidirectional IoT communication,” IEEE Transactions on Communications, 2021.

相关成果：（3） Energy-efficient NOMA for LiFi-IoT

User pairing:

◆ Channel-based user pairing

$$h_1^b \leq \cdots \leq h_k^b \leq \cdots \leq h_{2N}^b$$

◆ QoS-based user pairing

$$\widetilde{R}_1^b \geq \cdots \geq \widetilde{R}_k^b \geq \cdots \geq \widetilde{R}_{2N}^b$$

◆ Adaptive channel and QoS-based user pairing

Algorithm 1 Adaptive channel and QoS-based user pairing

Input: h_k^b, $\widetilde{R}_k^b$, P_z, $b \in \{\mathrm{d}, \mathrm{u}\}$, $k = 1, 2, \cdots, 2N$
Output: optimal user pair $U_i^{b,\mathrm{opt}}$, $i = 1, 2, \cdots, N$
Step 1: channel-based user pairing
Sort $\{h_k^b\}_{k=1,2,\cdots,2N}$ in ascending order
Divide the sorted users into $G_1^{b,\mathrm{c}}$ and $G_2^{b,\mathrm{c}}$
Obtain $U_i^{b,\mathrm{c}} = \{G_1^{b,\mathrm{c}}(i), G_2^{b,\mathrm{c}}(i)\}$, $i = 1, 2, \cdots, N$
Calculate $P_{\mathrm{elec,min}}^{b,\mathrm{c}}$ using $U_i^{b,\mathrm{c}}$ and (18)
Step 2: QoS-based user pairing
Sort $\{\widetilde{R}_k^b\}_{k=1,2,\cdots,2N}$ in descending order
Divide the sorted users into $G_1^{b,\mathrm{q}}$ and $G_2^{b,\mathrm{q}}$
Obtain $U_i^{b,\mathrm{q}} = \{G_1^{b,\mathrm{q}}(i), G_2^{b,\mathrm{q}}(i)\}$, $i = 1, 2, \cdots, N$
Calculate $P_{\mathrm{elec,min}}^{b,\mathrm{q}}$ using $U_i^{b,\mathrm{q}}$ and (18)
Step 3: adaptive selection
for $i = 1$ to N **do**
  if $P_{\mathrm{elec,min}}^{b,\mathrm{c}} \leq P_{\mathrm{elec,min}}^{b,\mathrm{q}}$ **then**
    $U_i^{b,\mathrm{opt}} = U_i^{b,\mathrm{c}}$
  else
    $U_i^{b,\mathrm{opt}} = U_i^{b,\mathrm{q}}$
  end if
end for

C. Chen, et al., "NOMA for energy-efficient LiFi-enabled bidirectional IoT communication," IEEE Transactions on Communications, 2021.

VLC物理层多用户接入技术

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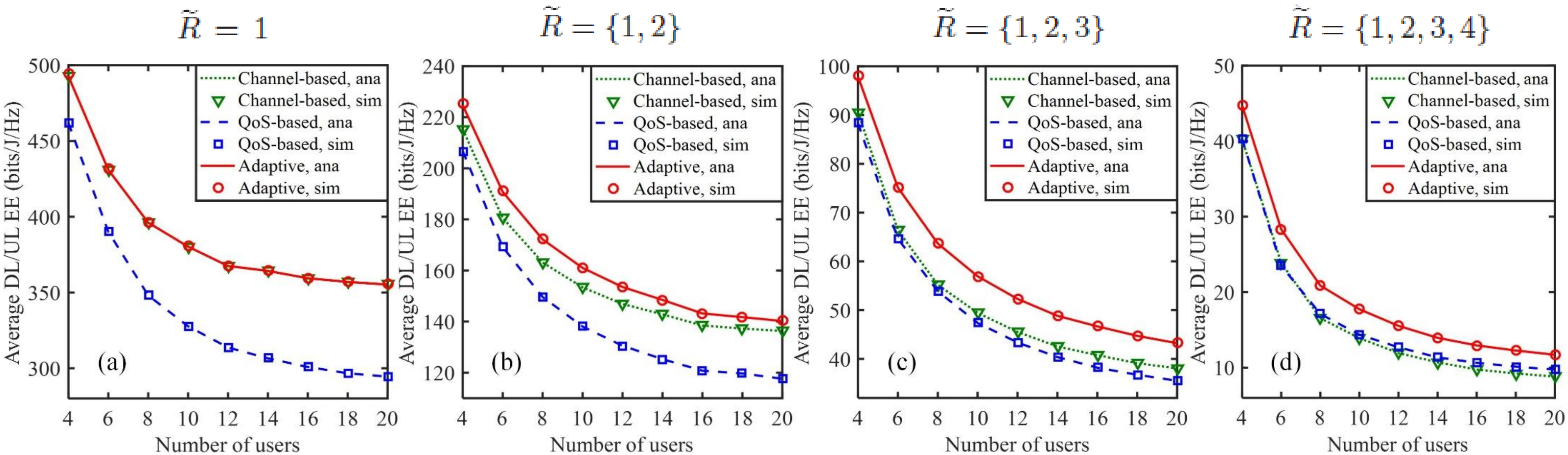
相关成果：（3） Energy-efficient NOMA for LiFi-IoT

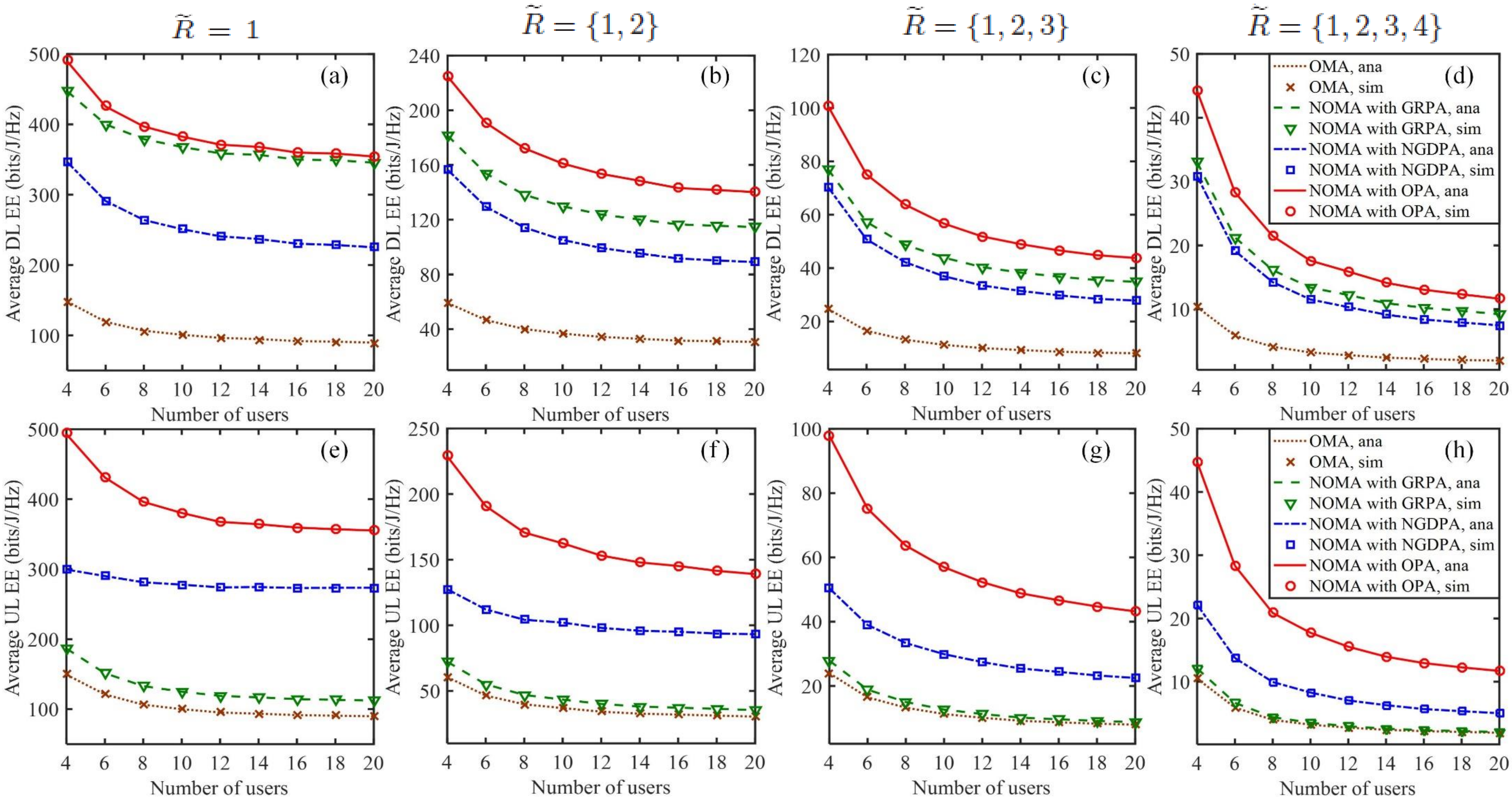


Adaptive channel and QoS-based user pairing outperforms individual channel-based or QoS-based user pairing, especially for diverse QoS requirements

C. Chen, et al., “NOMA for energy-efficient LiFi-enabled bidirectional IoT communication,” IEEE Transactions on Communications, 2021.

VLC物理层多用户接入技术

相关成果：（3） Energy-efficient NOMA for LiFi-IoT



The proposed NOMA with OPA achieves the best EE in both downlink and uplink

C. Chen, et al., "NOMA for energy-efficient LiFi-enabled bidirectional IoT communication," IEEE Transactions on Communications, 2021.

机遇：VLC被广泛誉为6G以及IoT通信的潜在关键技术

6G总体愿景与潜在关键技术
白皮书

IMT-2030 (6G)推进组
2021年6月

四 6G潜在关键技术

智能全息无线电基于微波光子天线阵列的相干光上变频，可实现信号的超高相干性和高并行性，有利于信号直接在光域进行处理和计算，解决智能全息无线电系统的功耗和时延挑战。

智能全息无线电在射频全息成像和感知等领域已有一定程度的研究，但在无线通信领域的应用仍面临许多挑战和难点，主要包括智能全息无线电通信理论和模型的建立；基于微波光子技术的连续孔径有源天线阵与高性能光计算之间的高效协同、透明融合和无缝集成等硬件及物理层设计相关等问题。

（四）太赫兹与可见光通信技术

1.太赫兹通信技术

太赫兹频段（0.1~10THz）位于微波与光波之间，频谱资源极为丰富，具有传输速率高、抗干扰能力强和易于实现通信探测一体化等特点，重点满足Tbps量级大容量、超高传输速率的系统需求。

太赫兹通信可作为现有空口传输方式的有益补充，将主要应用在全息通信、微小尺寸通信（片间通信及纳米通信）、超大容量数据回传、短距超高速传输等潜在应用场景。同时，借助太赫兹通信信号进行高精度定位和高分辨率感知也是重要应用方向。

太赫兹通信需要解决的关键核心技术及难点主要包括以下几个方面。收发架构设计方面，目前太赫兹通信系统有三类典型的收发架构，包括基于全固态混频调制的太赫兹系统、基于直接调制的太赫兹系统和基于光电结合的太赫兹系统，小型化、低成本、高效率的太赫兹收发架构是亟待解决的技术问题。射频器件方面，太赫兹通信系统中的主要射频器件包括太赫兹变频电路、太赫兹混频器、太赫兹倍频器和太赫兹放大器等。当前太赫兹器件的工作频点和输出功率仍然难以满足低功耗、高效率、长寿命等商用需求，需要探索基于锗化硅、磷化铟等新型半导体材料的射频器件。基带信号处理方面，太赫兹通信系统需要实时处理Tbps量级的传输速率，突破低复杂度、低功耗的先进高速基带信号处理技术是太赫兹商用的前提。太赫兹天线方面，目前高增益天线主要采用大尺寸的反射面天线，需要突破小型化和阵列化的太赫兹超大规模天线技术。此外，为了实现信道表征和度量，还需要针对太赫兹通信不同场景进行信道测量与建模，建立精确实用化的信道模型。

2.可见光通信技术

可见光通信指利用从400THz到800THz的超宽频谱的高速通信方式，具有无需授权、高保密、绿色和无电磁辐射的特点。

可见光通信比较适合于室内的应用场景，可作为室内网络覆盖的有效补充，此外，也可应用于水下通信、空间通信等特殊场景以及医院、加油站、地下矿场等电磁敏感场景。

当前大部分无线通信中的调制编码方式、复用方式、信号处理技术等都可应用

18

6G总体愿景与潜在关键技术白皮书，中国信通院IMT-2030(6G)推进组，2021年6月6日.

总结与展望

机遇：VLC被广泛誉为6G以及IoT通信的潜在关键技术

总结与展望

挑战：VLC的推广和落地实用还任重道远！

总结与展望

潜在研究方向：

人工智能机器学习方法在VLC中的应用	水下/矿下/轨道交通等特殊应用场景的VLC
基于无人机的应急照明和VLC一体化	基于可见光的数能同传 (SLIPT)
基于智能反射表面/可重构智能表面的新型VLC	基于新型索引调制的VLC传输

智能LiFi实验室
Lab of Intelligent LiFi

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Visible Light Communication (VLC)

Guest Editor:

Dr. Chen Chen
School of Microelectronics and Communication Engineering, Chongqing University, Chongqing 400044, China

c.chen@cqu.edu.cn

Deadline for manuscript submissions:
31 December 2021

Message from the Guest Editor

This special issue focuses on visible light communications (VLC) and spans both MDPI *Sensors* and *Photonics*. We welcome submissions on any topic in VLC, with particular interest in the following, nonexclusive, list of principal topics:

- Multitechnology VLC/x integration and transceiver design;
- High data rate links, channel modelling, and digital signal processing;
- Conventional and non-orthogonal modulation,

Journals / Sensors / Special Issues / Visible Light Communication (VLC)

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Interests: visible light communication; LiFi; Internet of Things; digital signal processing

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