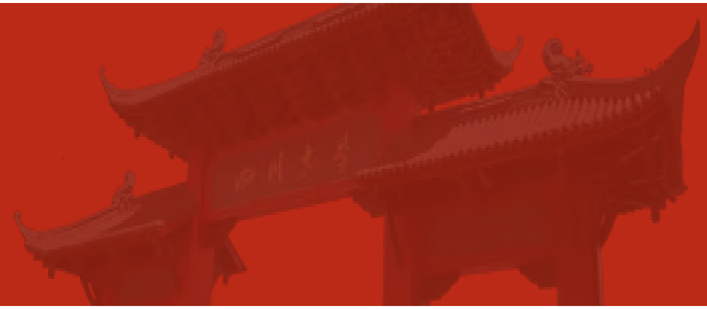
基于空间光合成调制的可见光通信技术



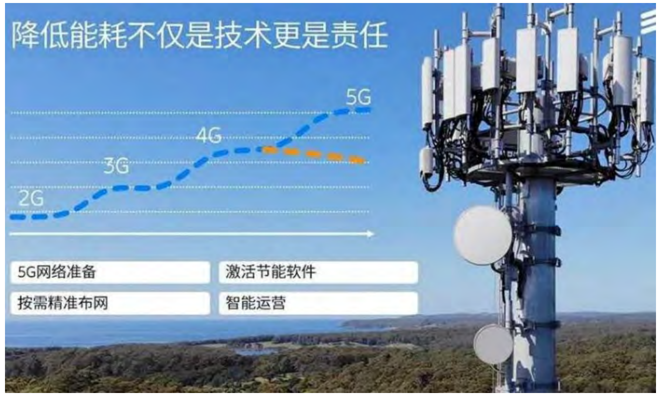
杨彦兵 副研究员

四川大学计算机学院/工业互联网研究院

2021年6月

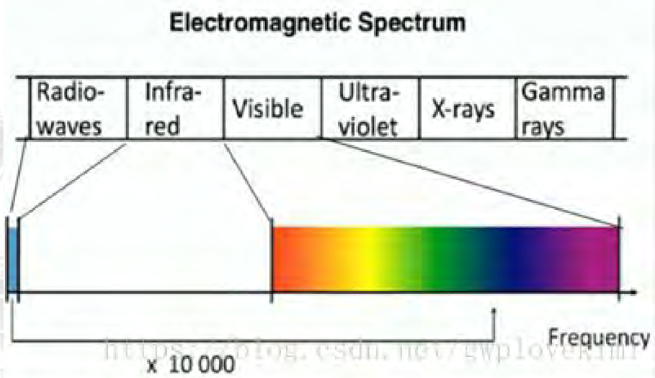
研究背景及意义

频谱资源枯竭



高能耗

部分场景无法使用



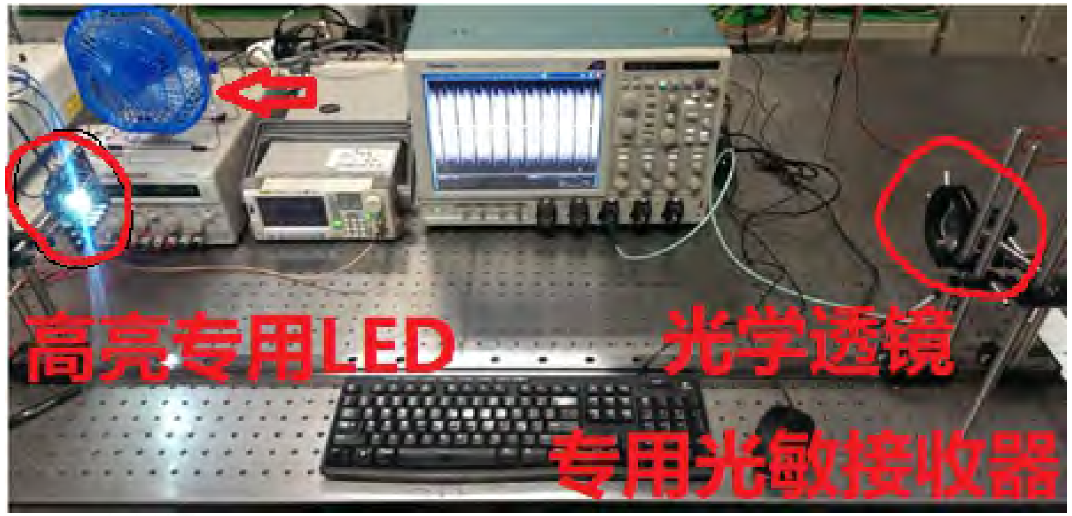
频谱资源丰富

能量消耗用于照明

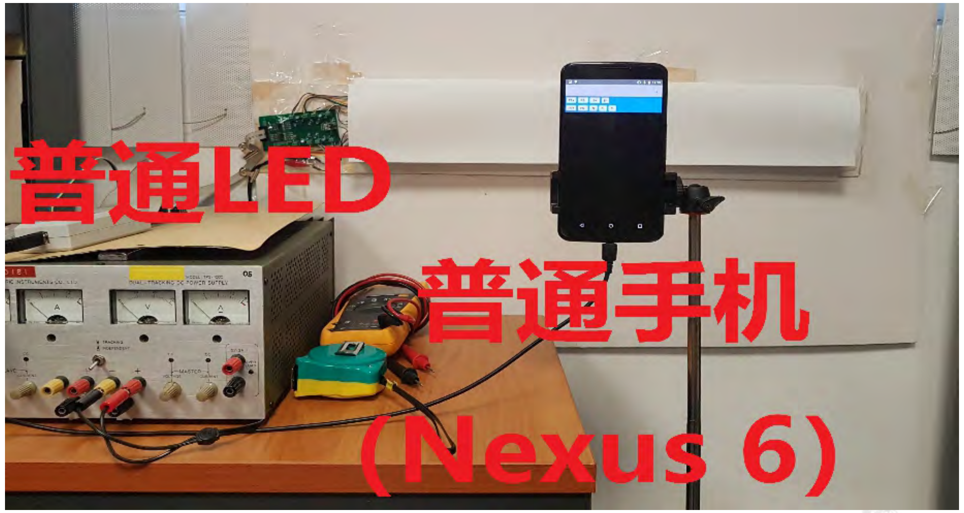
支持辐射敏感场景

可见光通信是新一代高带宽、绿色通信技术！

可见光通信类型



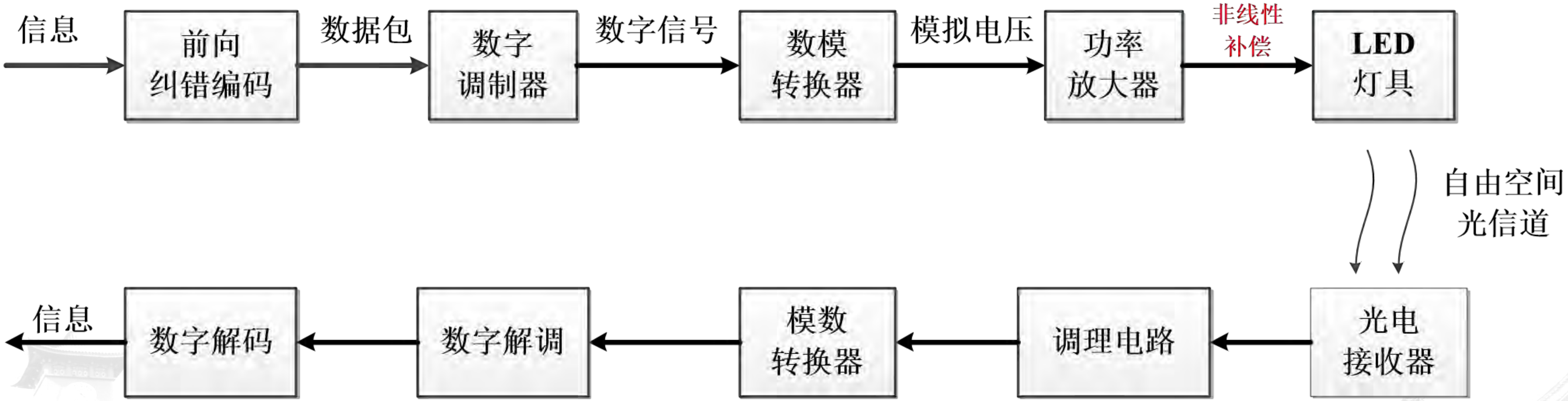
基于专用光敏器件的可见光通信系统

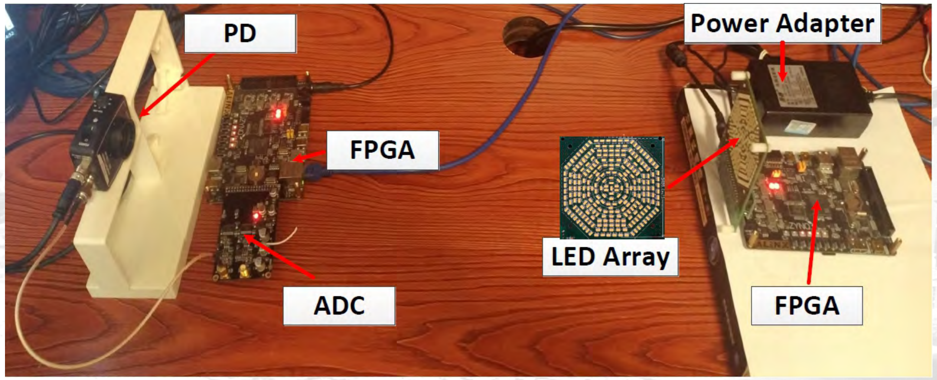


基于相机的OCC系统

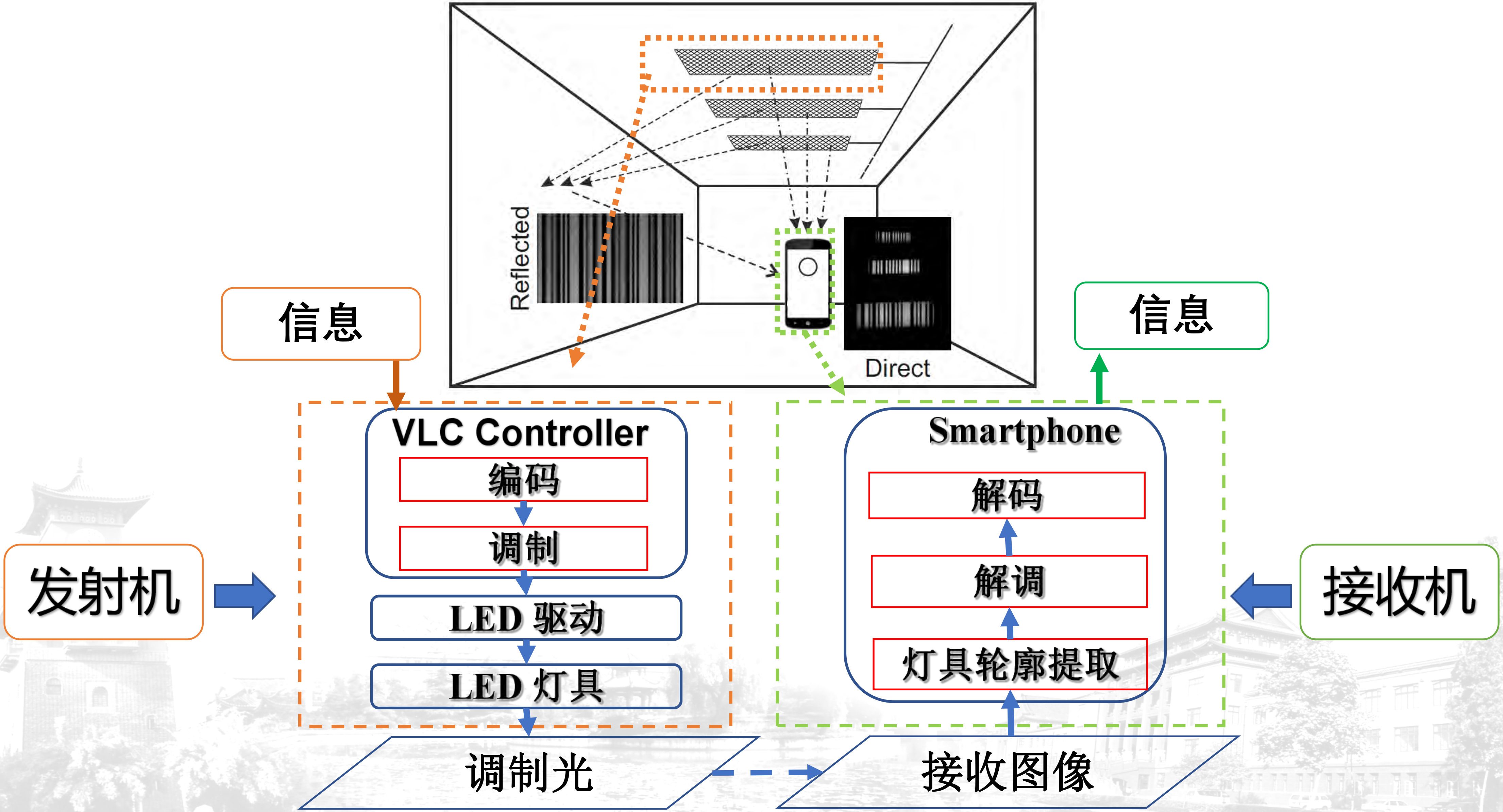
OCC： Optical Camera Communication（光学相机通信）

基于专用光敏器件的可见光通信





光学相机通信


Reflected
Direct
信息
信息
VLC Controller
编码
调制
LED 驱动
LED 灯具
Smartphone
解码
解调
灯具轮廓提取
发射机
接收机
调制光
接收图像

相机光通信潜在应用场景

□ 取代部分纸质二维码

- ➢ 内容单一固定 更换造成资源浪费大
- ➢ 信息容量小 无法满足未来大数据需要
- ➢ 样式不够美观 视觉表现“先天不足”
- ➢ 隐私易被泄露、信息安全性不高的问题

“扫光”点餐/支付应用

□ 泛在互联

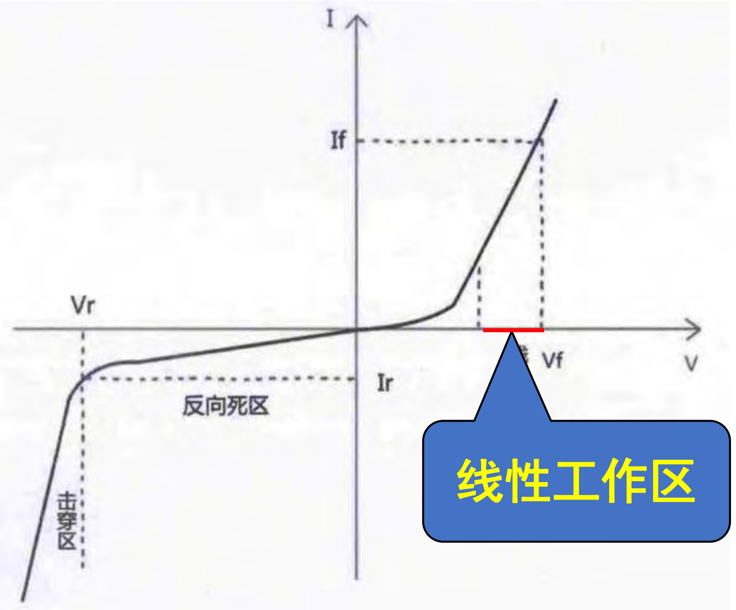
工业互联

车路协同

……

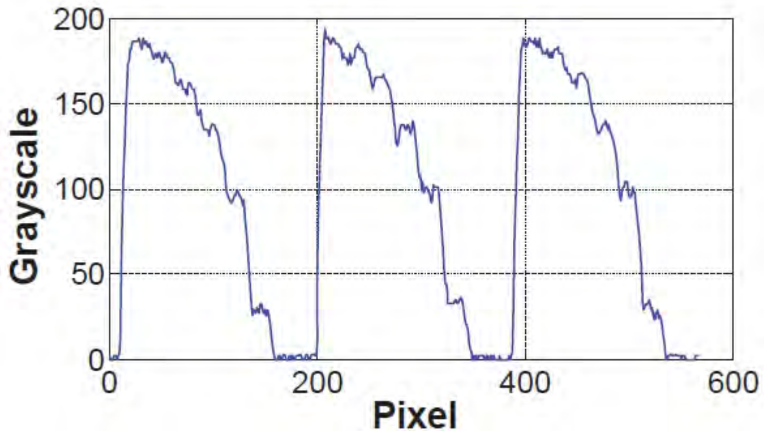
可见光通信面临的挑战

挑战1：LED非线性与线性区间狭窄

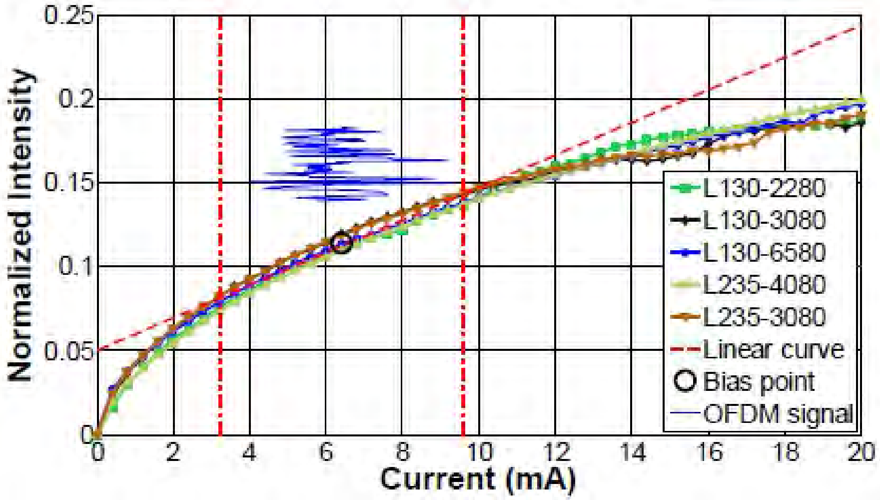


LED 芯片I-V曲线

导致



PAM8信号严重畸变



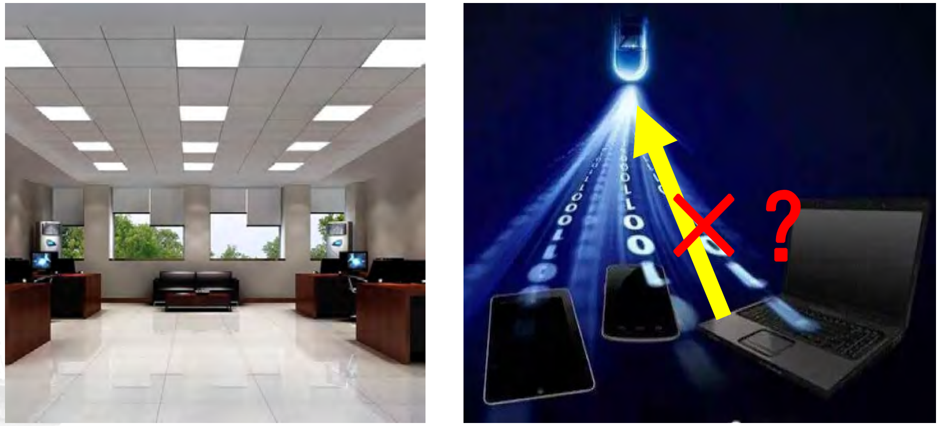
可用幅度调制范围狭窄

LED非线性严重影响信号质量和调制效率。

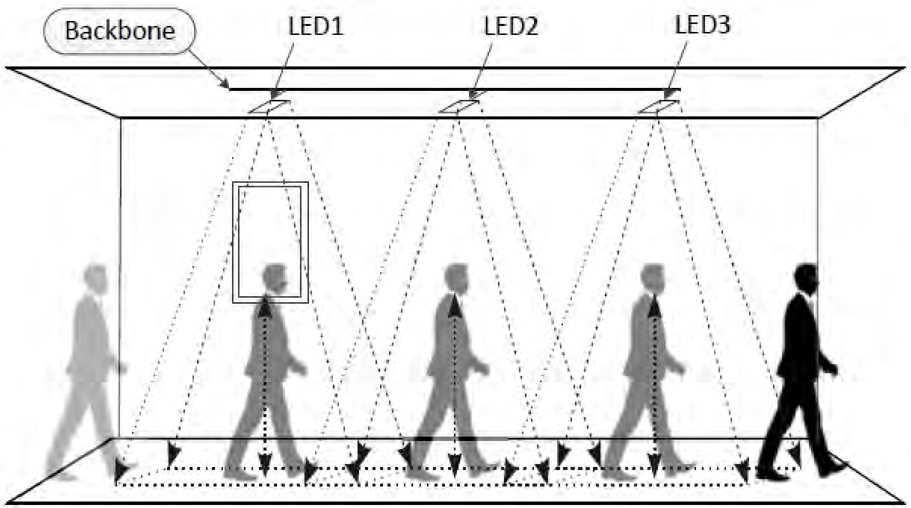
可见光通信面临的挑战

四川大學 SICHUAN UNIVERSITY

挑战2：单个LED照明区域小且无上行链路，难以支持移动用户



单灯覆盖区域小且缺乏上行链路



移动用户连续通过3个LED照明区域

覆盖区域小且缺乏上行链路，移动用户难以获得连续的通信服务。

挑战3：通信与照明协同

可见光通信需兼顾照明需求，如灯光亮暗等。

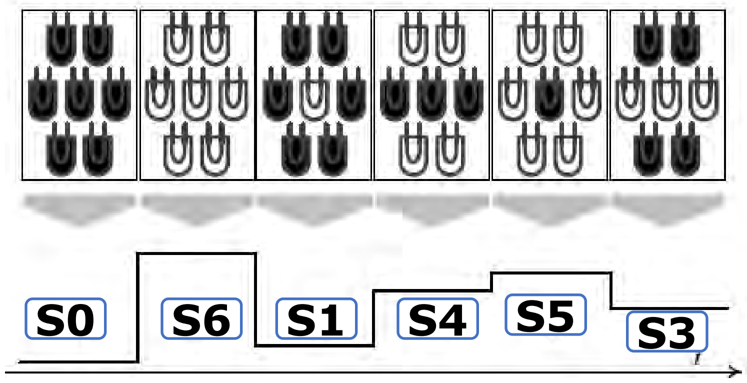
挑战	LED非线性	移动用户支持	通信照明协同
解决方案	基于空间光合成的数字-光直接转换技术	基于可见光传感的用户检测技术	支持亮度调节的调制技术

基于空间光合成的数字-光直接转换技术

依托基于空间合成的数字-光直接转换技术，发表了以下三篇论文：

- Yanbing Yang, Jun Luo, Chen Chen, Wen-De Zhong and Liangyin Chen. **SynLight**: Synthetic Light Emission for Fast Transmission in COTS Device-enabled VLC. In Proceedings of the 38th IEEE Conference on Computer Communications, IEEE INFOCOM'19, pp. 1297-1305, Paris, France,2019.
- Yanbing Yang, Chen Chen, Pengfei Du, Xiong Deng, Jun Luo, Wen-De Zhong, and Liangyin Chen. Low Complexity **OFDM VLC** System Enabled by Spatial Summing Modulation. Optics Express, 27(21):30788–30796, 2019.
- Chao Hu, Chen Chen, Min Guo, Yanbing Yang[#], Jun Luo and Liangyin Chen. Optical Spatial Summing based **NOMA** with Fine-grained Power Allocation for VLC-enabled IoT Applications. Optics Letters, 45(17), 4927-4930, 2020.

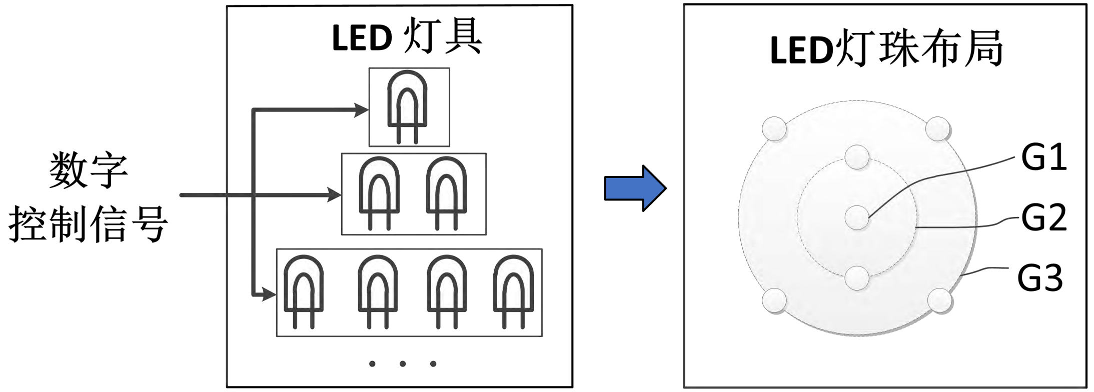
基于空间光合成的数字-光直接转换技术



The idea of synthetic light emissions: the emissions from multiple LEDs are controlled so that the spatially synthesized intensities represent respective modulation symbols.

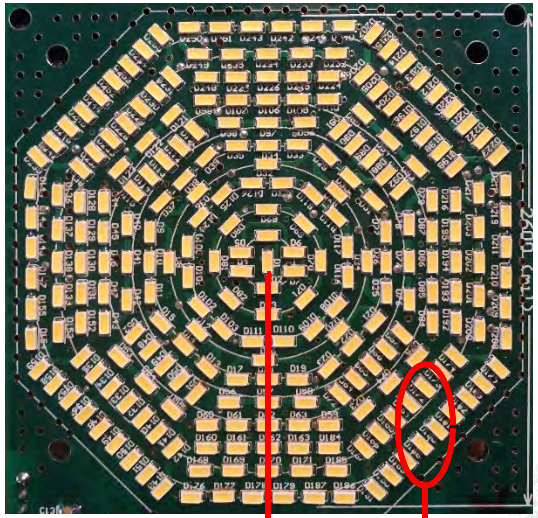
论文：IEEE INFOCOM19、IEEE TMC、OSA OE、OSA OL

1. 将LED灯具上的LED灯珠拆分为一系列灯组，降低控制复杂度



灯珠按照2的幂次方分组　　同心圆盘排列

包含255颗灯珠发射机

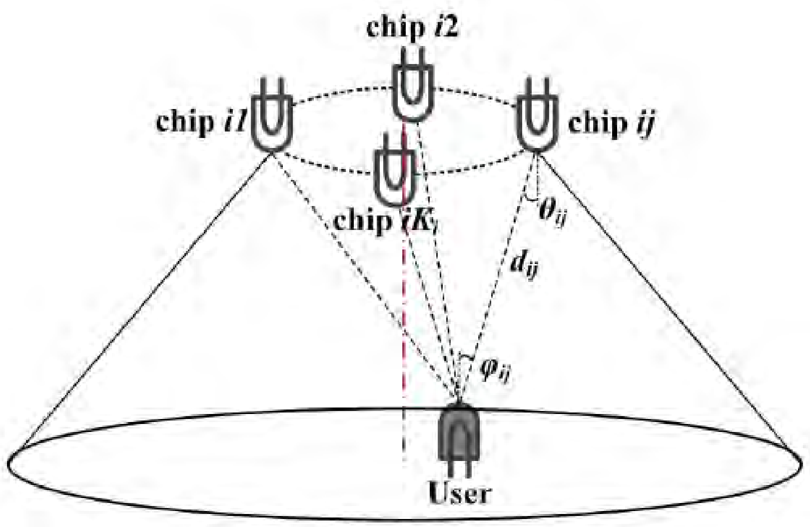


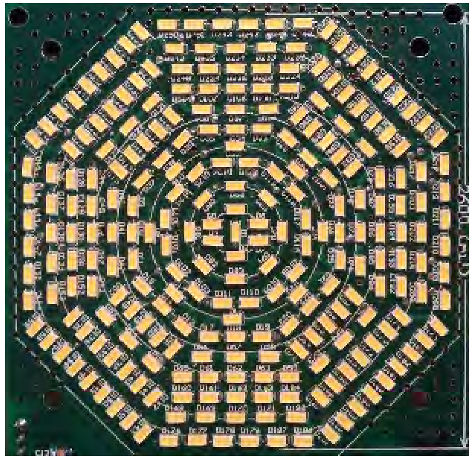
第1组：1颗灯珠

第8组：128颗灯珠

第N组包含2^（N-1）颗灯珠，并且第一组在圆心位置，第N组在圆盘最外层。

2. 空间光合成建模





第i组第j颗灯珠与用户之间的信道增益：

$$h_{ij} = \frac{(m+1)A}{2\pi d_{ij}^2}\cos^m(\theta_{ij})\cos(\varphi_{ij}),$$

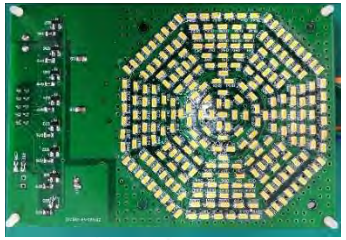
所有灯珠合成光强：

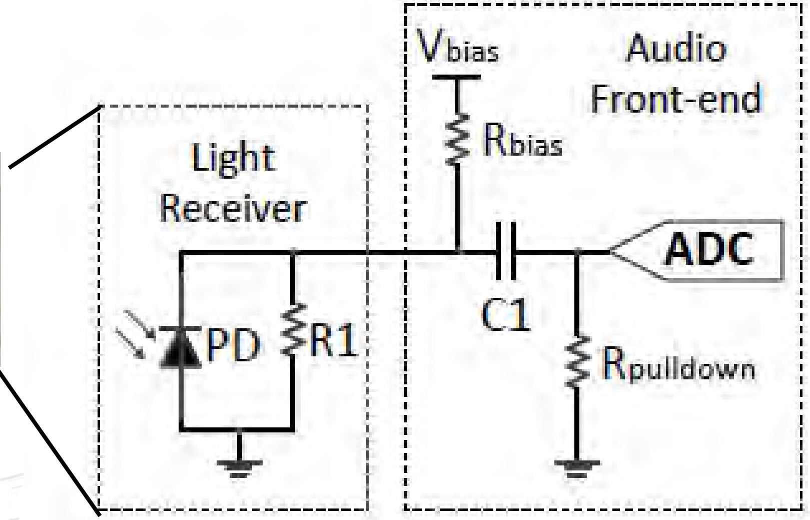
$$y(t) = \sum_{i=1}^{G}\sum_{j=1}^{K_i} Rh_{ij}x_{ij}(t) + n(t),$$

论文：IEEE INFOCOM19、IEEE TMC、OSA OE、OSA OL

SynLight Prototype

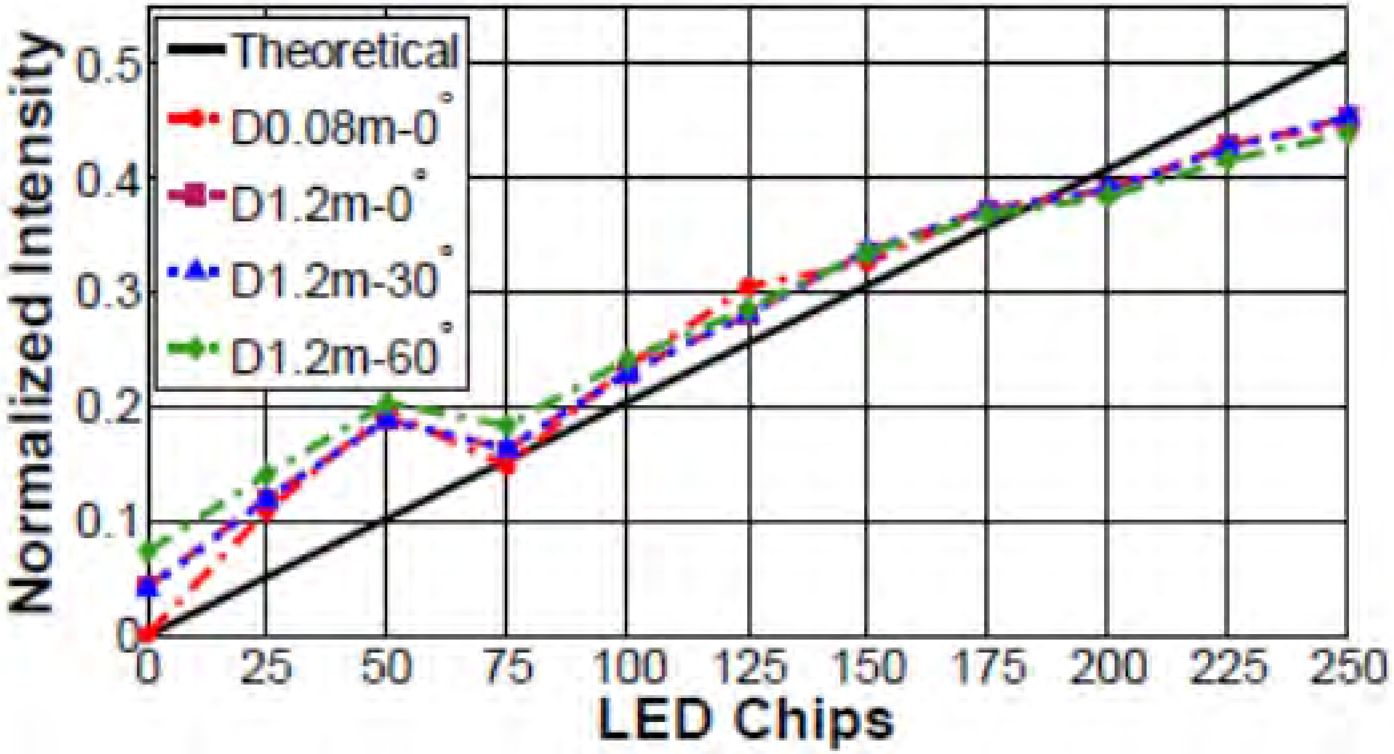
- SynLight's transmitter integrates **COTS components** onto a 4-layer PCB with a size of 10 cm × 7 cm.
- A photodiode SD3421 is used as the receiver front-end and interfaced to a Nexus 6 smartphone.





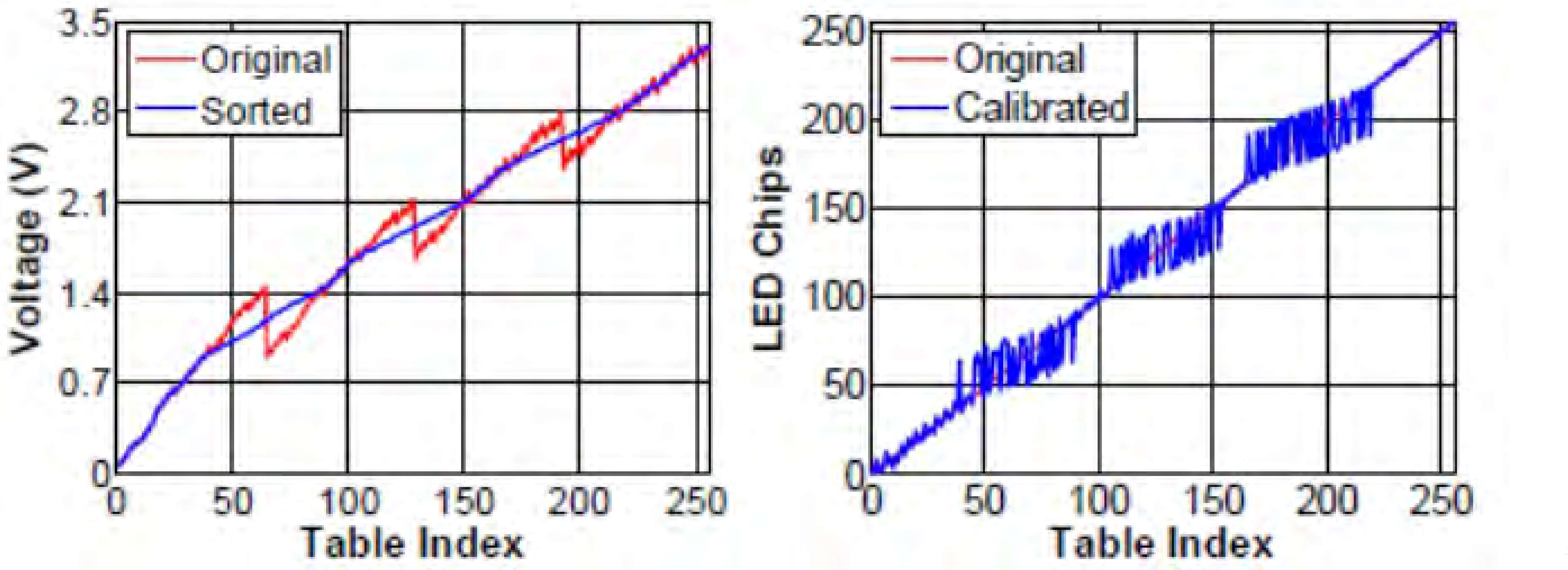
SynLight's transmitter (left) and receiver (right)

➢Nonlinear Output Caused by LED Diversity.



The differences between theoretical analysis and realistic measurements are mainly due to component diversity and circuit configurations.

➢Adaptively Calibrated Emissions.



(a) RLIs before/after sorting. (b) Codebook calibration.

RLIs: Received Light Intensities

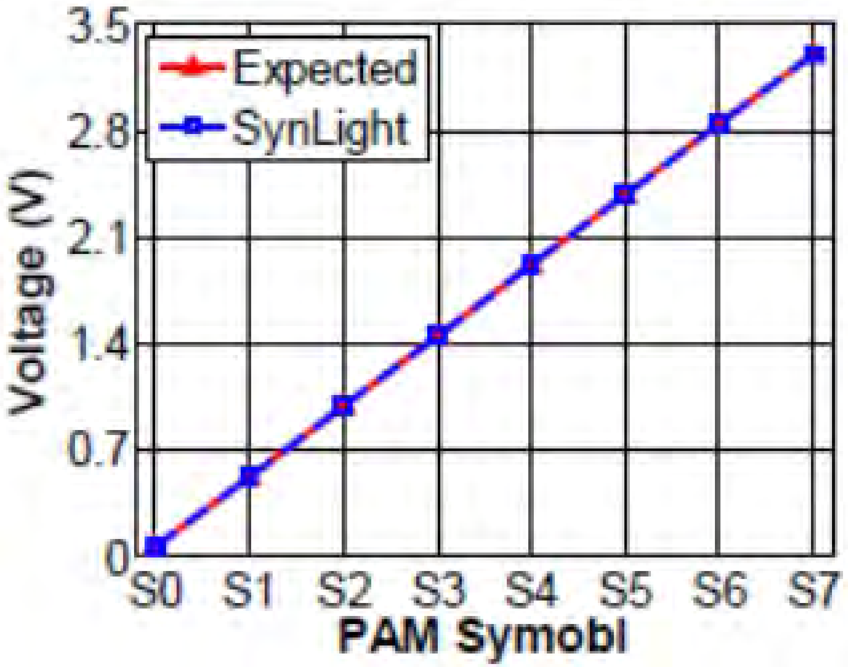
➢Adaptively Calibrated Emissions.

Algorithm 1: Adaptively calibration.

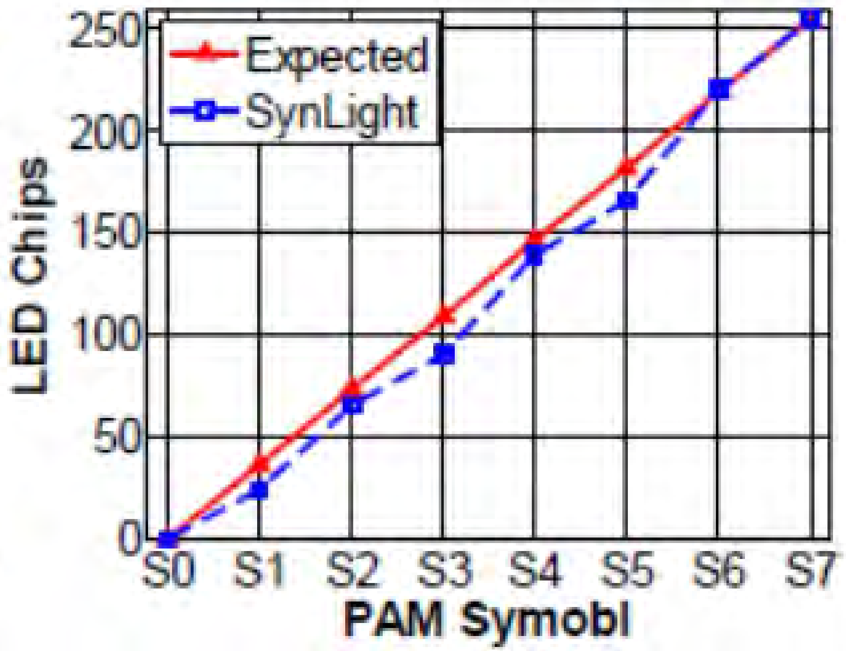
Data: M, N, $\boldsymbol{C}^{\text{PAM}}$, $\tilde{\boldsymbol{\ell}}$, ϵ
Result: $\boldsymbol{C}^{\text{PAM}}$
begin
- $\boldsymbol{C} \leftarrow \emptyset$; $\boldsymbol{\ell} \leftarrow \mathbf{0}$; $i \leftarrow 0$;
- **while** $i \leq N$ **do**
  - Switch i LED chips on,
  - measure and record ℓ_i as the RLI
  - $c_i \leftarrow i$; $\boldsymbol{C} \leftarrow \boldsymbol{C} \cup \{c_i\}$; $i \leftarrow i + 1$;
- Sort $\boldsymbol{\ell}$ ascendingly and adjust $\boldsymbol{C}$ accordingly
- $i \leftarrow 0$; $k \leftarrow 0$
- **while** $i \leq M$ **do**
  - **while** $|\tilde{\ell}_i - \ell_k| > \epsilon$ **do**
    - $k \leftarrow k + 1$;
  - $c_i^{\text{PAM}} \leftarrow c_k$; $i \leftarrow i + 1$;

四川大学 SICHUAN UNIVERSITY

➢Automatically Generated 8-PAM Symbols.



(a) 8-PAM symbols vs. RLIs.



(b) 8-PAM symbols vs. codes.

The transmitter can automatically generate PAM symbols based on the calibrated codebook.

➢ System Configuration

- Each packet contains 4 bytes payloads, an 8-bit *Packet Sequence Number* (PSN) and a header of 1 lowest symbol and 3 successive highest symbols.

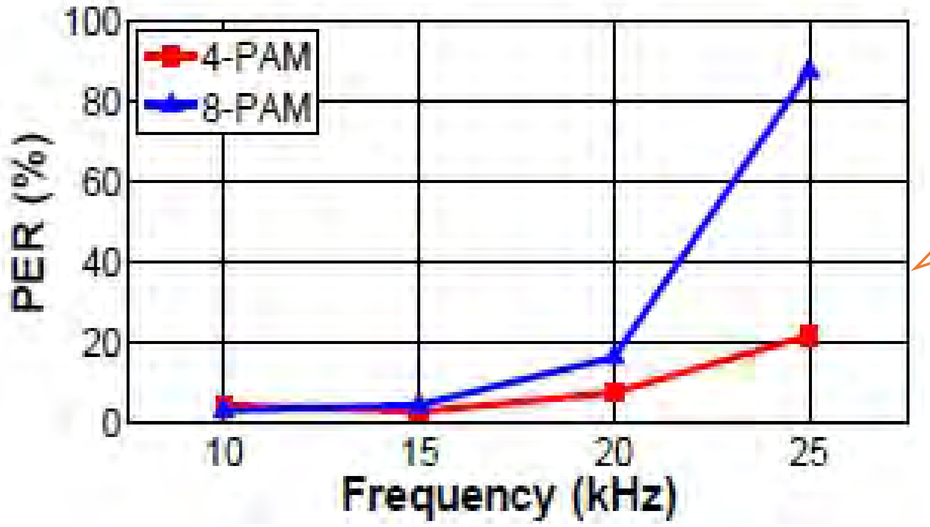
- Raptor coding as a *Forward Error Correction* (FEC) scheme and coding overhead is set as 25%.

- Each of our following experiments consists of 10 sessions and 320 packets (before FEC) are transmitted within each session.

Packet structure.

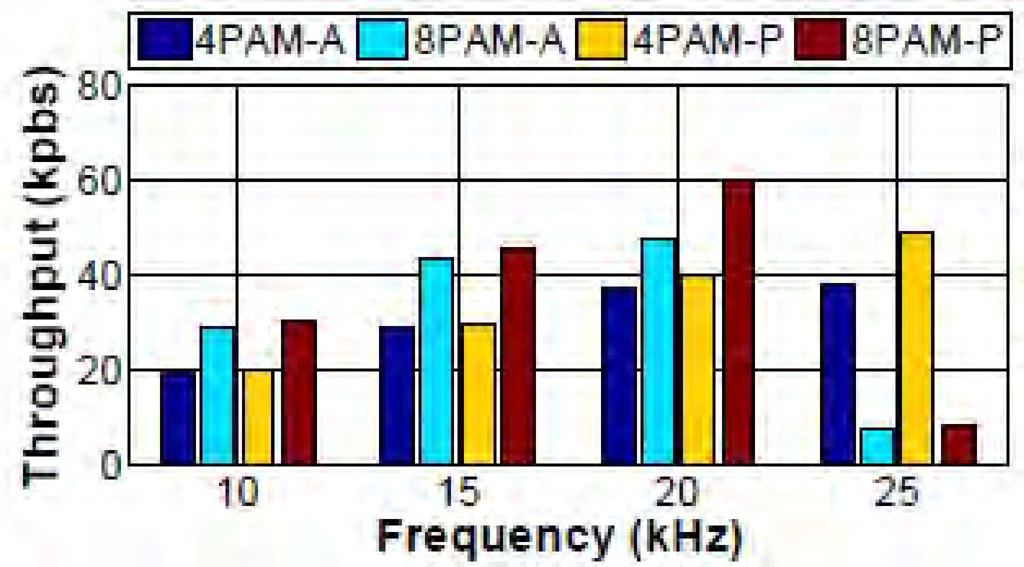
SICHUAN UNIVERSITY

➢ System Evaluation



(a) PER vs. Transmission Frequency.

Usable transmission frequency is limited by sample rate of smartphone's audio jack at 44.1 kHz.

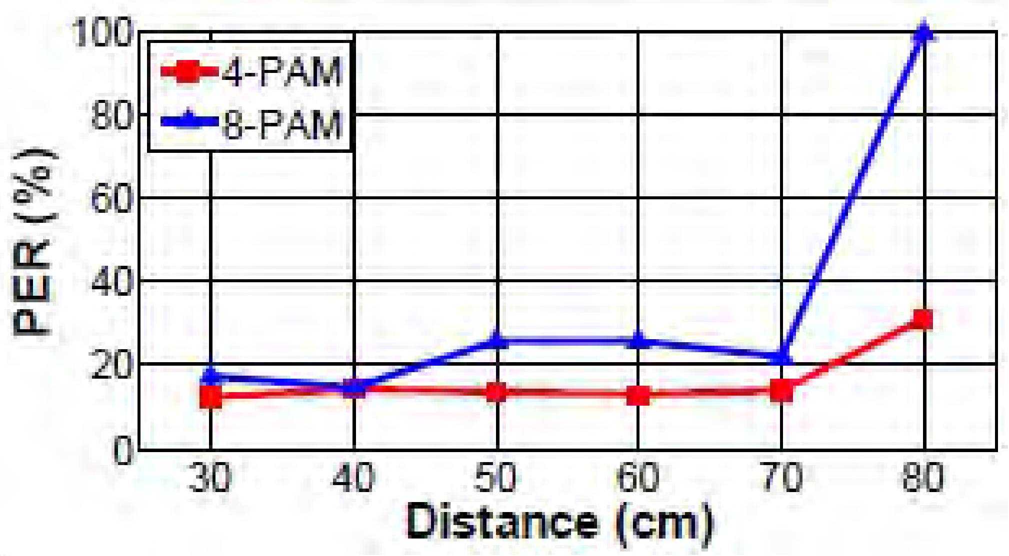


(b) Throughput vs. Transmission Frequency.

A maximum throughput up to 60 kbps given the sample rate limit.

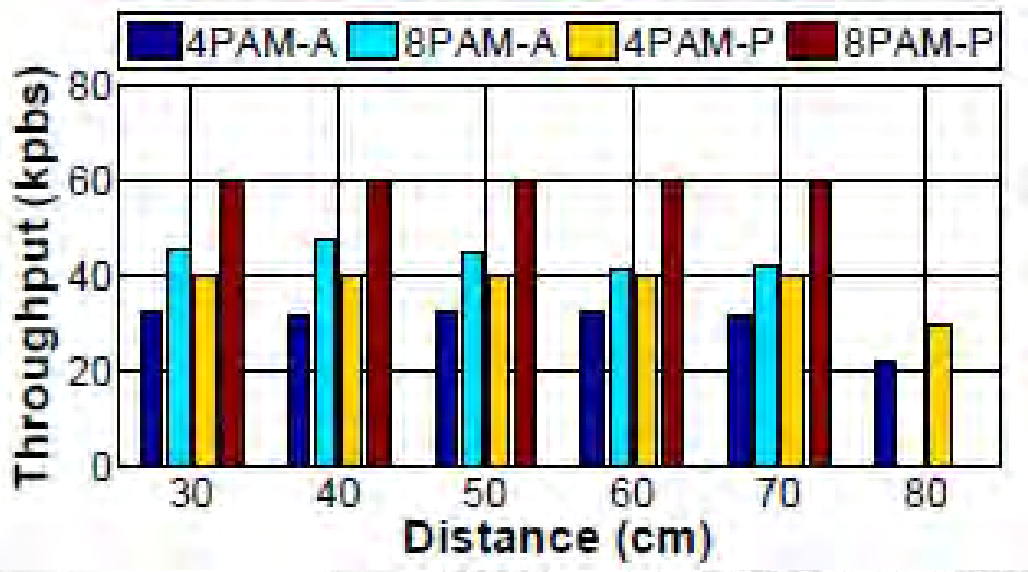
SICHUAN UNIVERSITY

➢ System Evaluation



(a) PER vs. Distance.

The simple receiver front-end confines communication distance, but it is feasible to largely extend it with an amplifier [2].

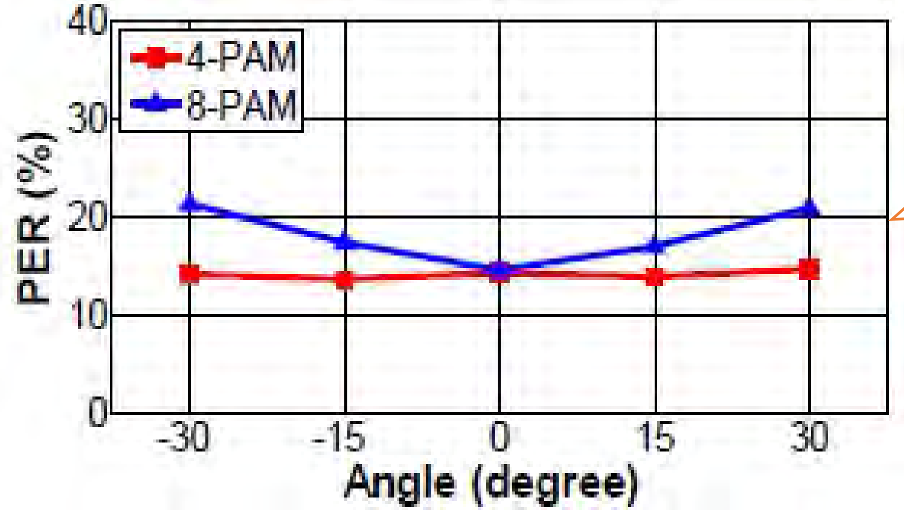


(b) Throughput vs. Distance.

SynLight achieves an average value over 40 kbps at 70 cm, which is more than 50 x of in [1] .

[1] S. Schmid, et al, "From Sound to Sight: Using Audio Processing to Enable Visible Light Communication," in 2014 IEEE Globecom Workshops, 2014, pp. 518–523.
[2] S. Verma, et al, "AudioDAQ: Turning the Mobile Phone's Ubiquitous Headset Port into a Universal Data Acquisition Interface," in Proc. of the 10th ACM SenSys, 2012, pp. 197–210.

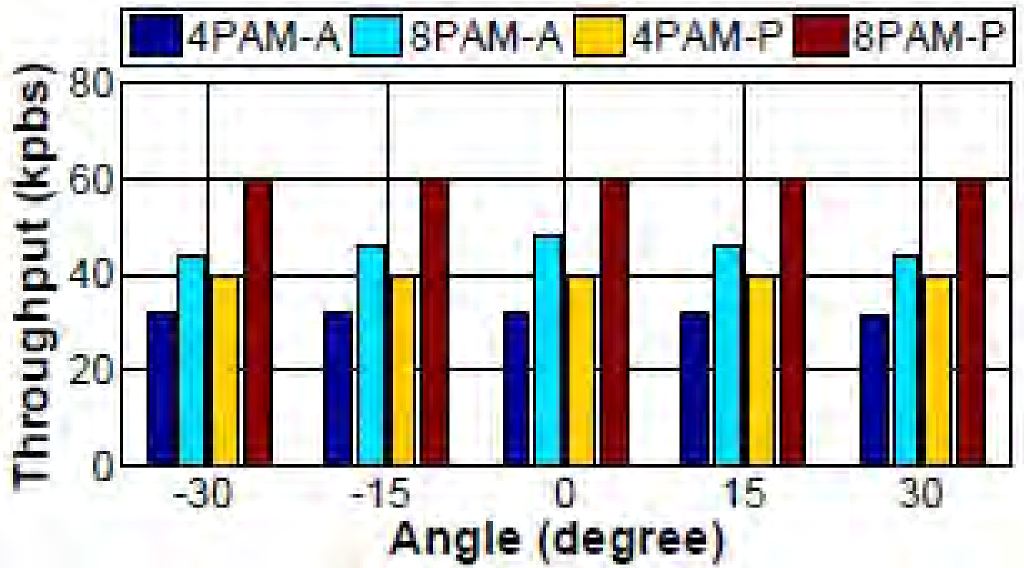
- System Evaluation



(a) PER vs. View Angle.

SynLight can support viewing angle with in [-30, 30]°.

Changing viewing angle does not obviously affect on throughput.

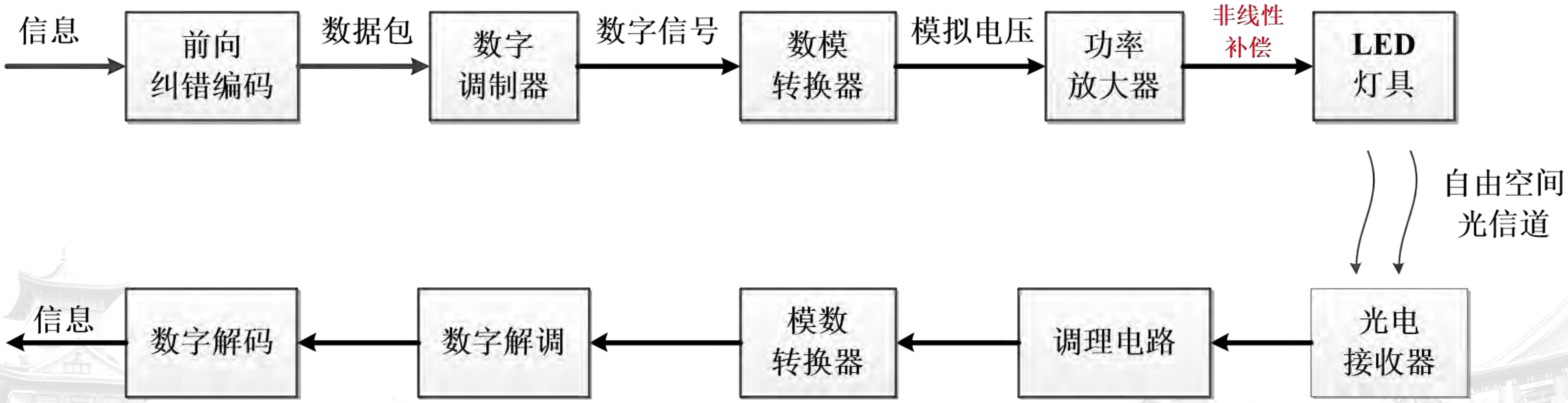


(b) Throughput vs. View Angle.

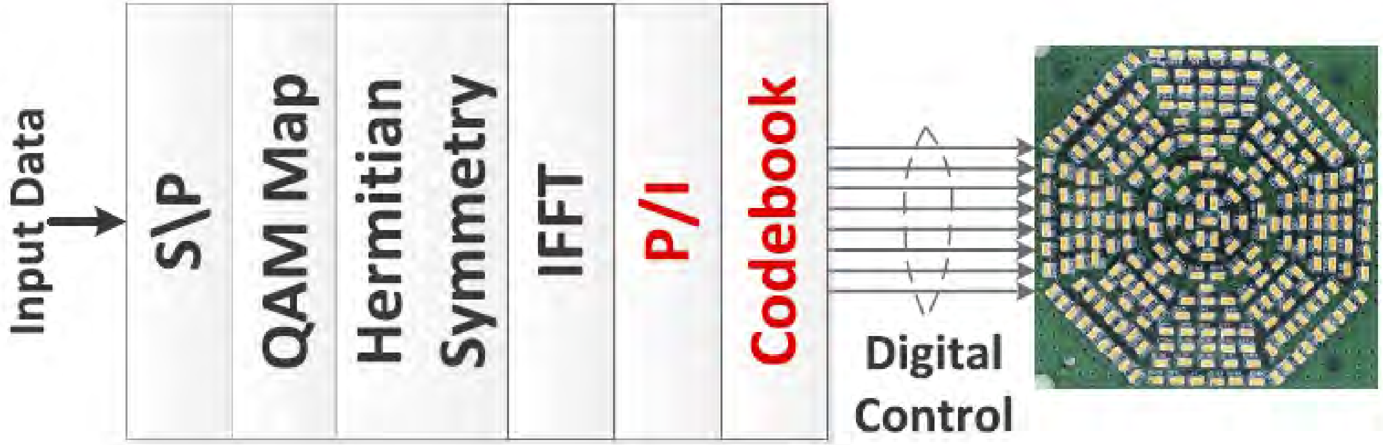
SynLight

- SynLight is a practical yet novel VLC system built upon COTS devices.
- A novel transmitter to generate high-order modulations without being troubled by LED nonlinearity.
- A calibration scheme to automatically handle the LED chip diversity in transmitter production.
- Extensive evaluations with SynLight prototype.

基于专用光敏器件的可见光通信



OFDM VLC

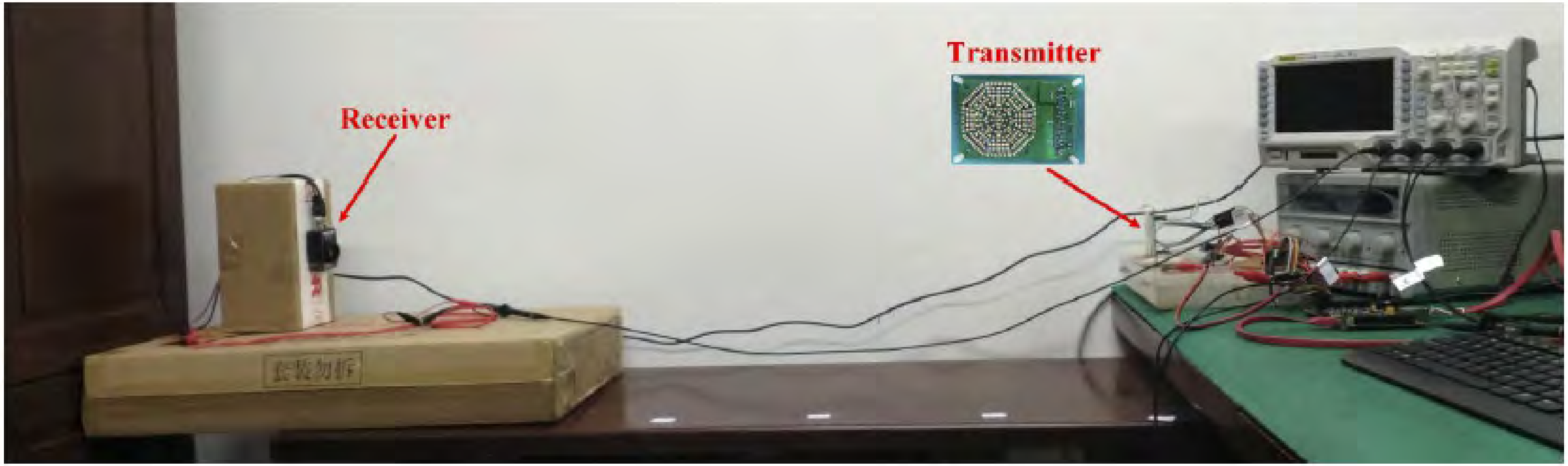


(a) Novel VLC Transmitter based on Spatial Summing.

(b) Traditional VLC Transmitter.

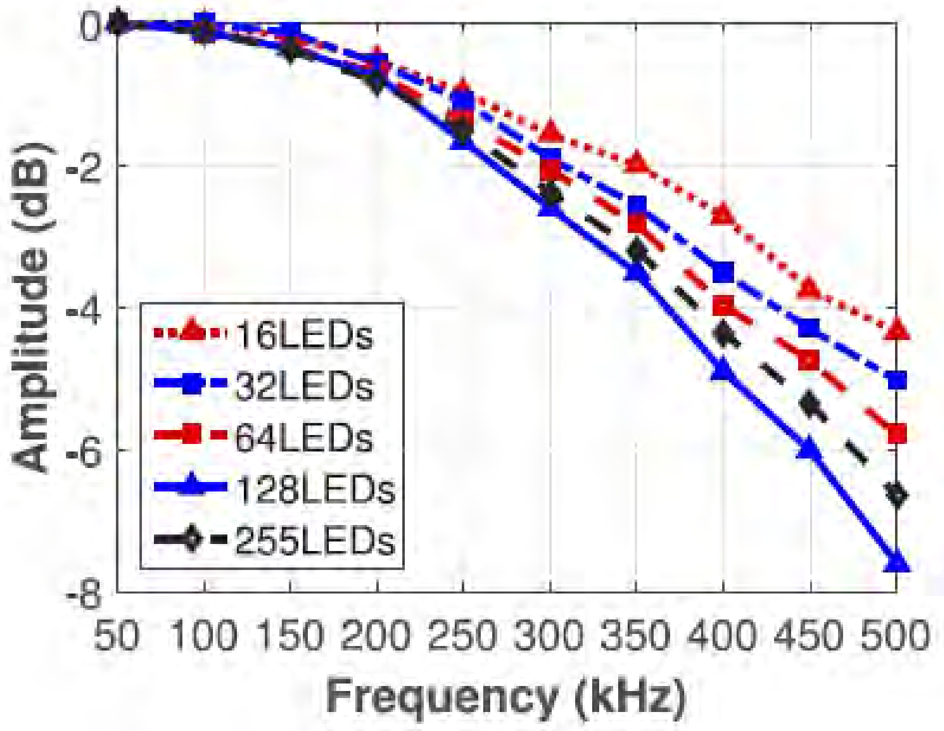
SICHUAN UNIVERSITY

➢ Experimental Testbed

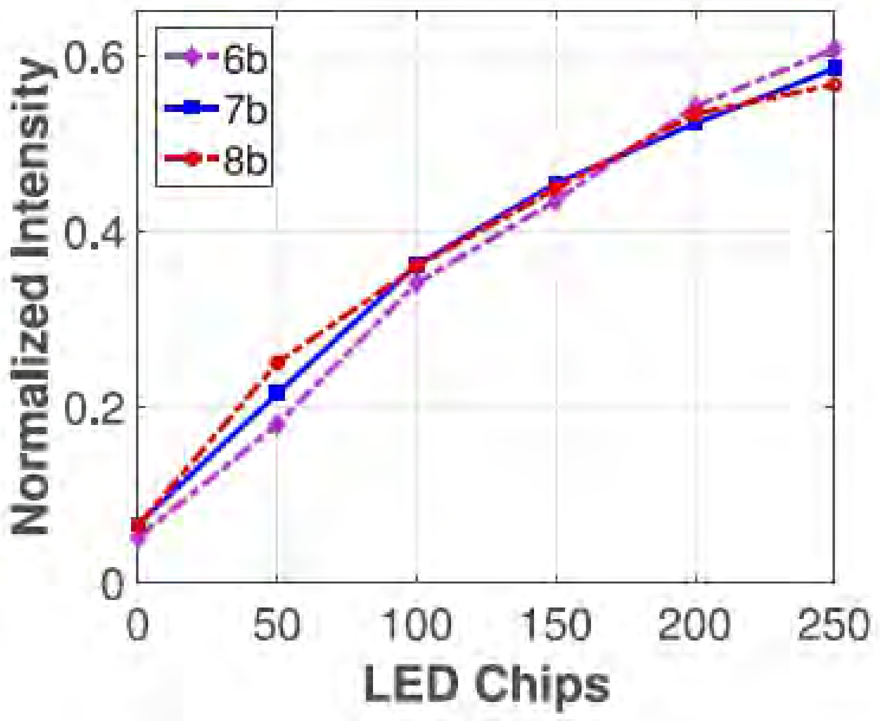


- We use a Xlinx FPGA to load the transmitting QAM-OFDM data-stream produced by MATLAB on a PC and generate the digital control signal for light modulation.
- A photodiode of Thorlabs PDA36A is used as the receiver, and the PDA36A' s output is recorded by an oscilloscope, and processed in MATLAB on a PC.

➢ Frequency response and output linearity



(a) Frequency response.

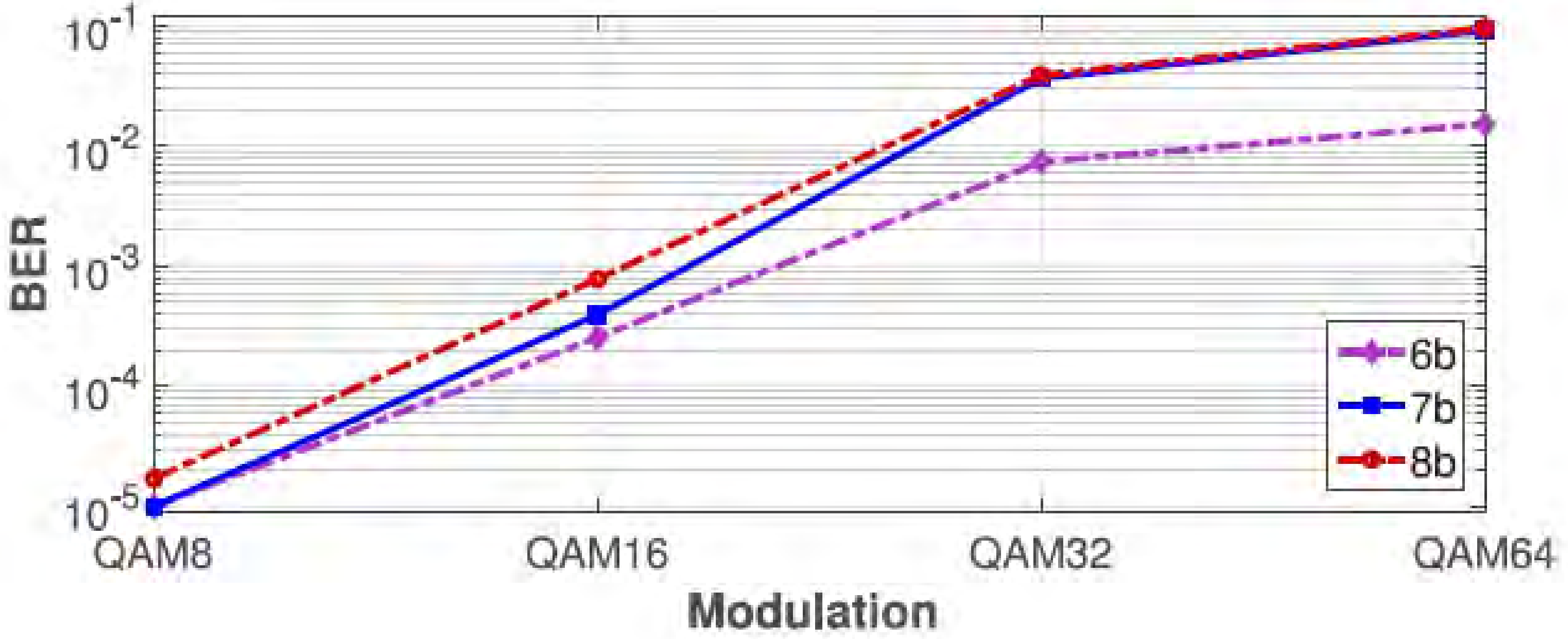


(a) Output linearity.

◆ **6b, 7b and 8b are different resolutions of 6, 7 and 8 bits.**

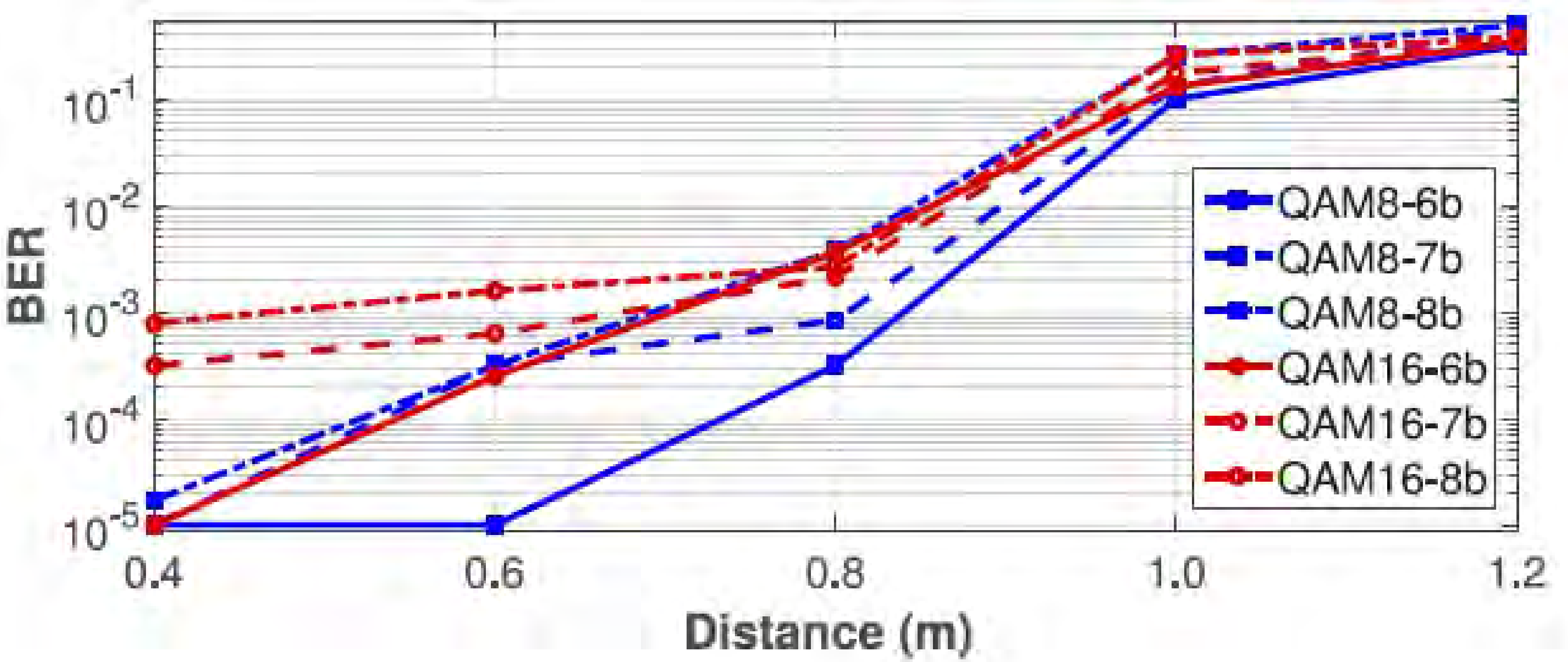
SICHUAN UNIVERSITY

- **Performance comparison under different quantization resolutions**



OFDM VLC

- BER vs. distance



The transmission frequency is configured as 300 kHz.

OFDM VLC

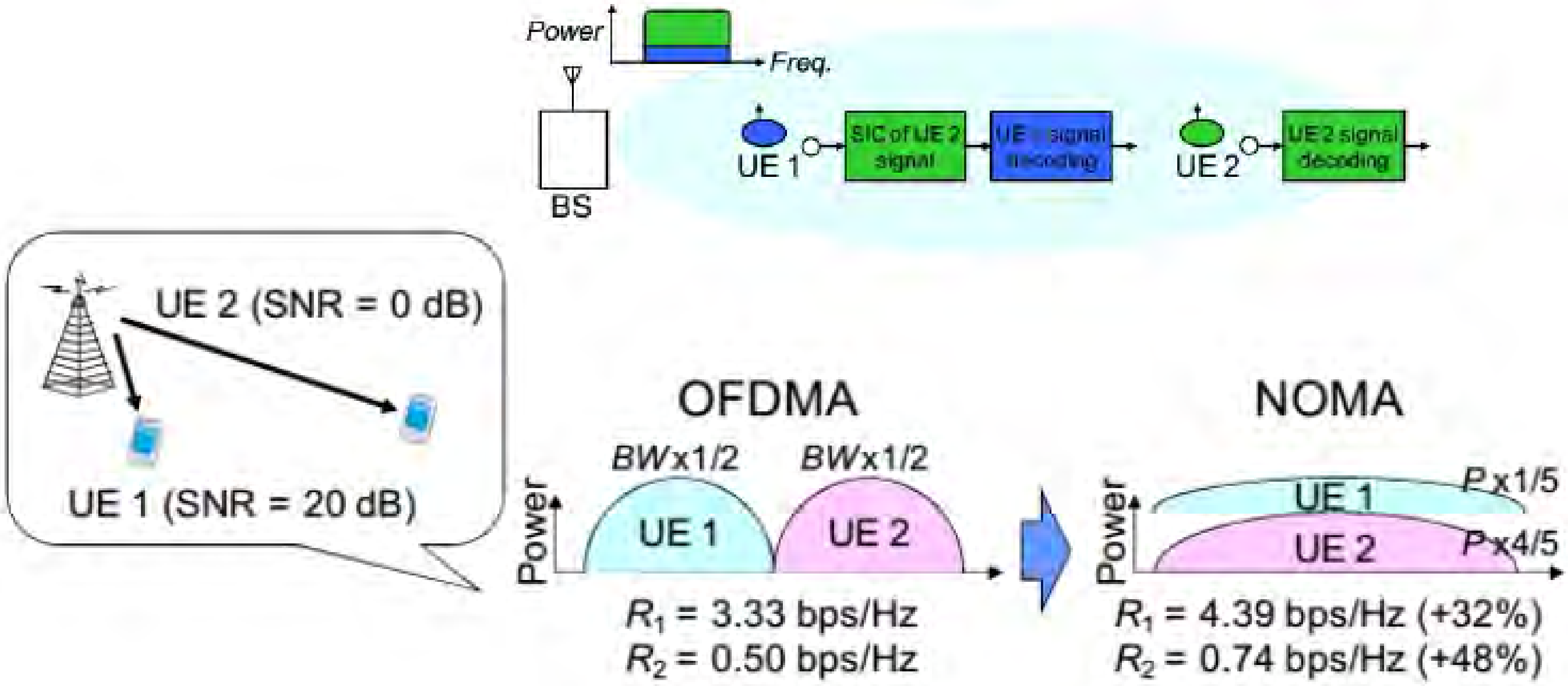
- A novel spatial summing based OFDM VLC system purely built on COTS devices is presented.

- By implementing a delicate yet low cost prototype, we have demonstrated the feasibility and promising performance of using spatial summing for an OFDM VLC system

- Extensive evaluations show the prototype can achieve very low BER of below of the FEC threshold of 3.8×10^{-3} for both QAM8 and QAM16 at a frequency of 300 kHz. it reveals the promising potential for delivering a data rate at hundred kbps level which is suitable for many IoT applications

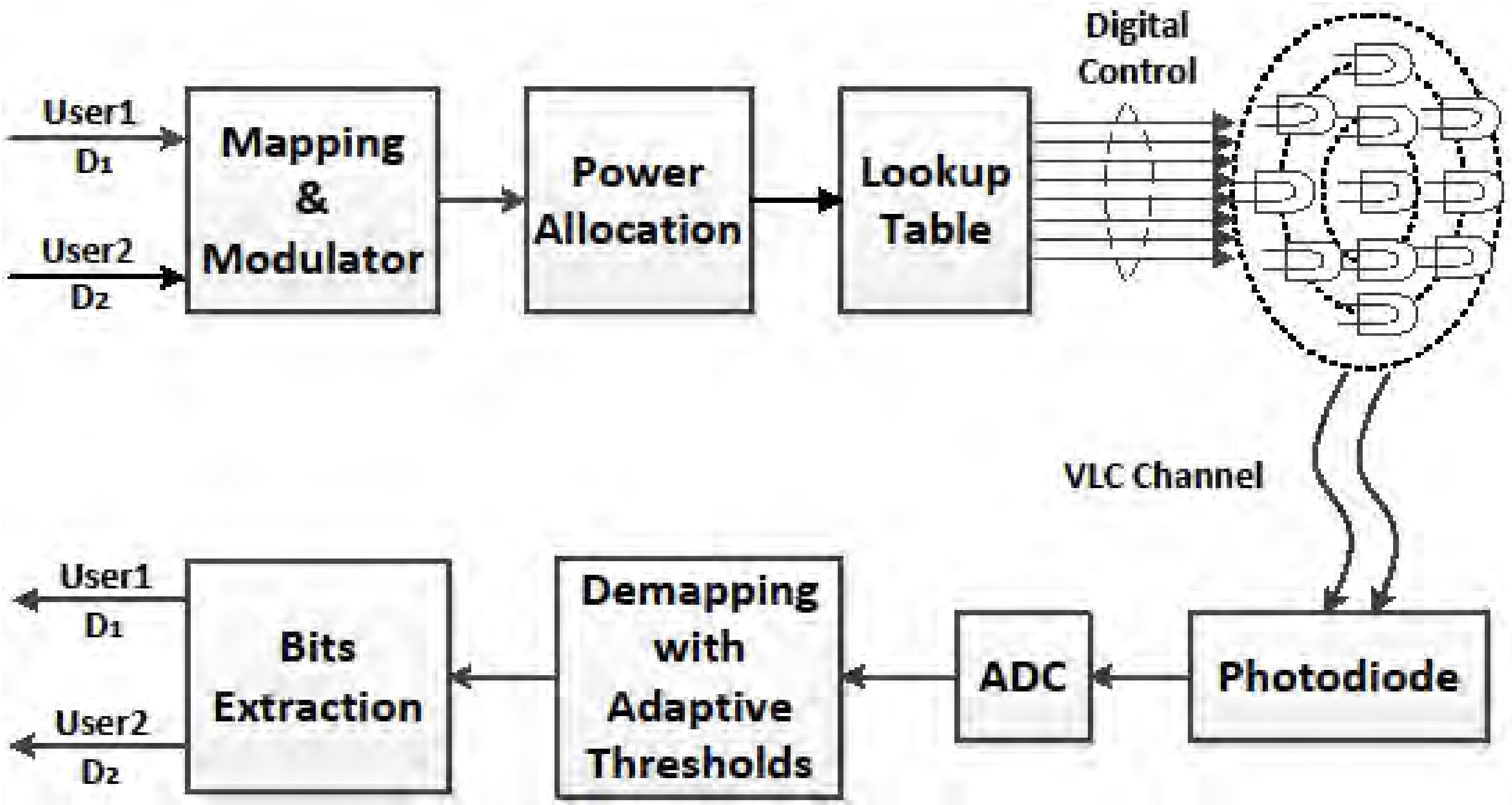
NOMA VLC

- **NOMA: non-orthogonal multiple access**
- **OMA: orthogonal multiple access**



NOMA achieves superior spectral efficiency compared to OMA.

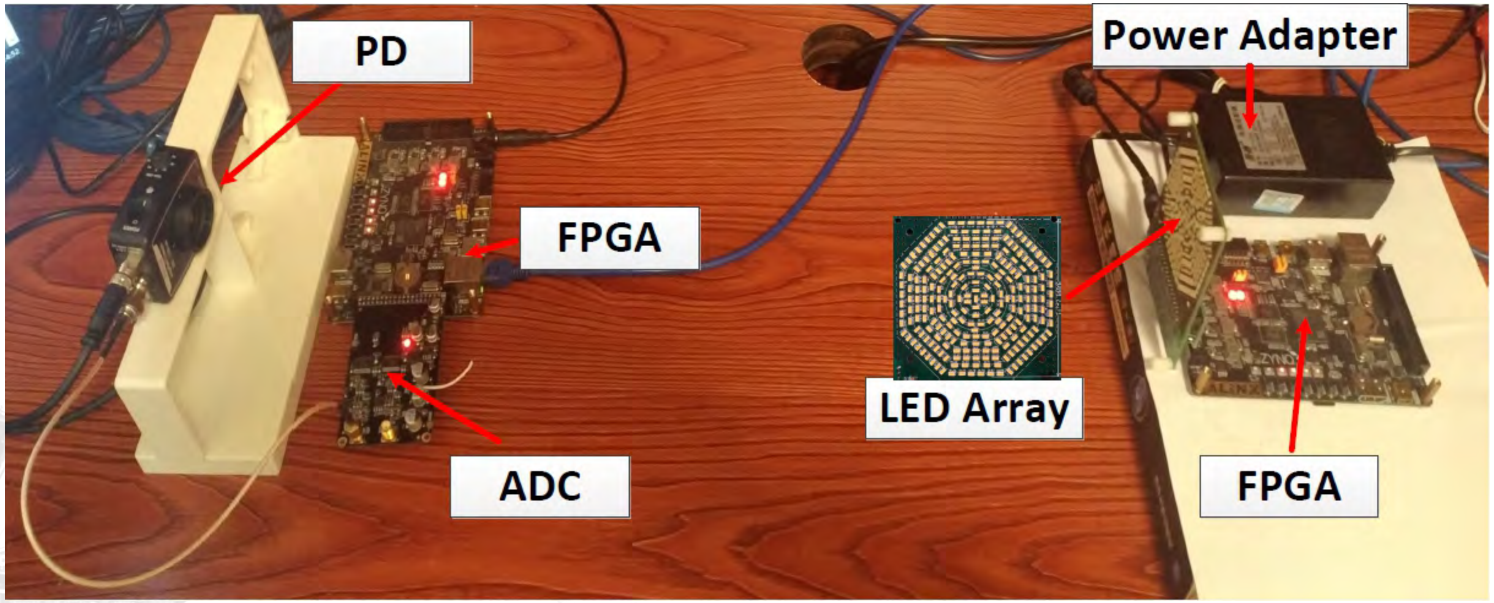
http://www.riazulislam.com/uploads/3/9/8/5/3985970/noma_tutorial.pdf



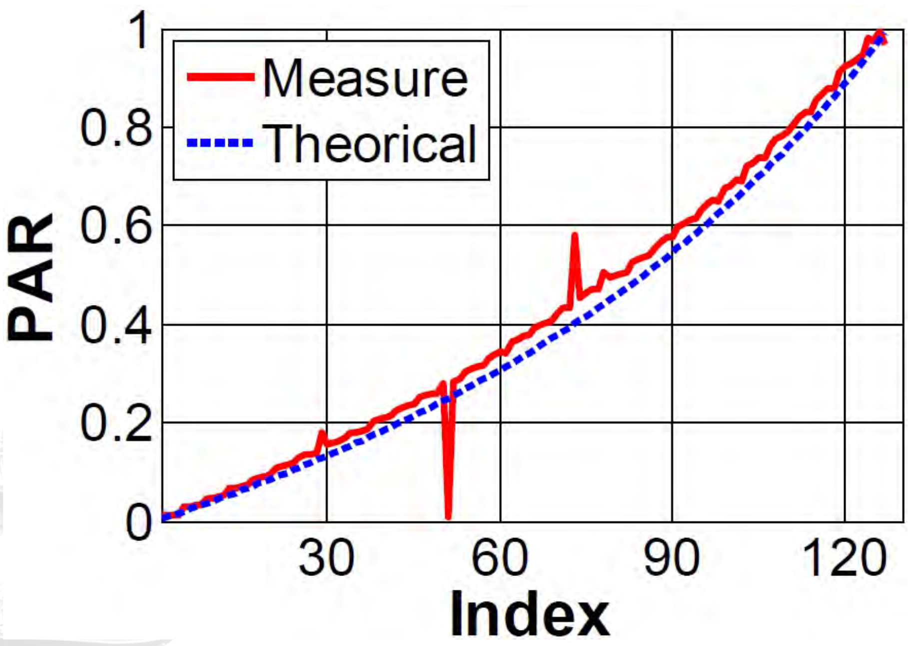
Block diagram of the proposed OSS-NOMA VLC system for two users.

NOMA VLC

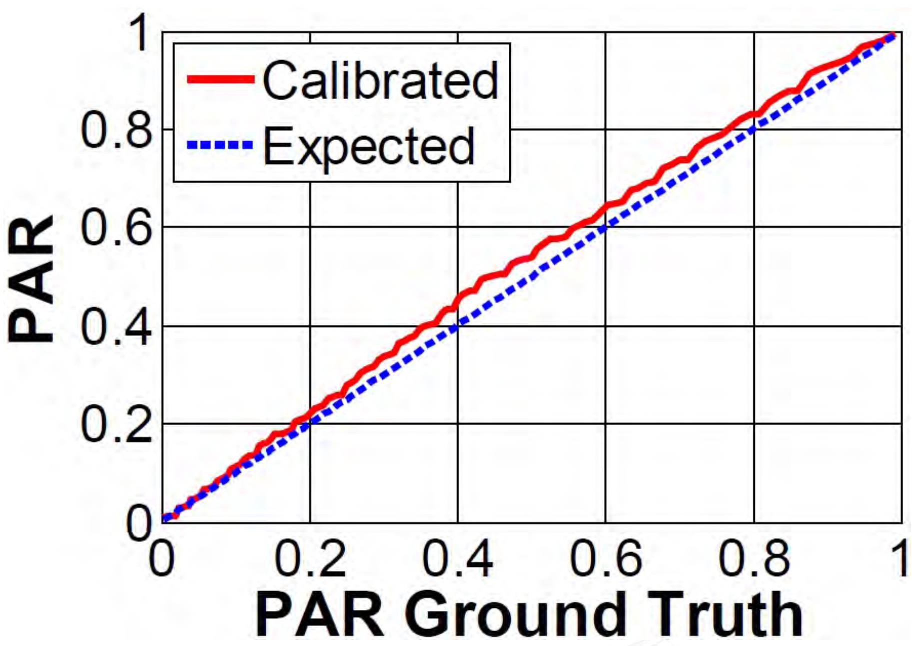
- Prototype



➢ **Adptive calibration for PAR table**



(a) Measured PAR.



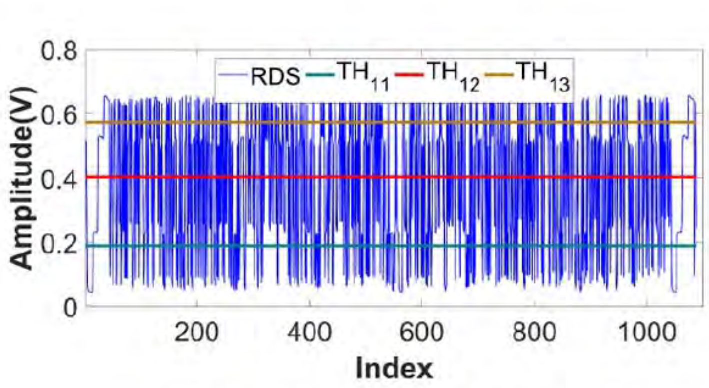
(a) Calibrated PAR table.

The power allocation ratio (PAR) is defined as α=P1/P2, where P1 and P2 are allocated powers for user1 and user2, respectively.

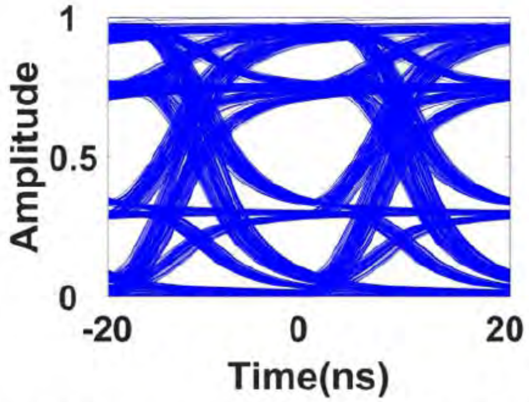
NOMA VLC

SICHUAN UNIVERSITY

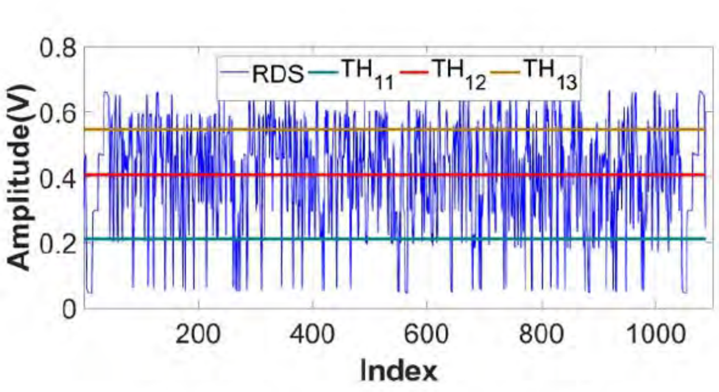
- **Demodulating and demapping for NOMA signals.**



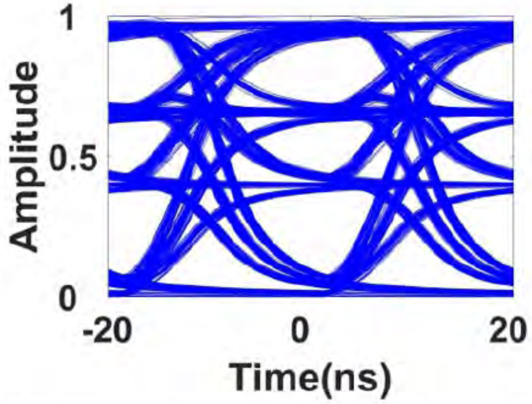
(a) Waveform with PAR=0.4



(b) Eye diagram with PAR=0.4

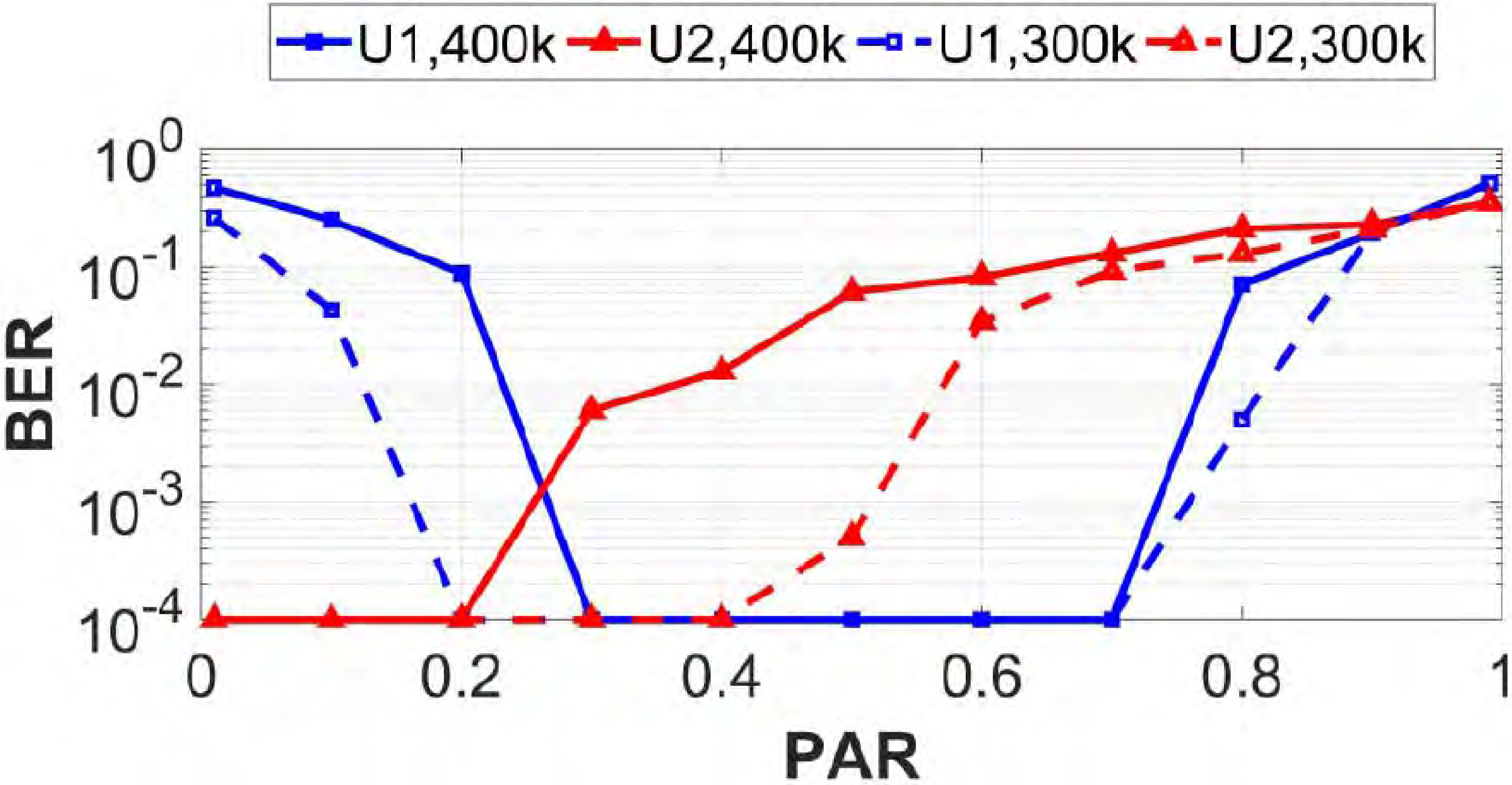


(c) Waveform with PAR=0.6



(d) Eye diagram with PAR=0.6

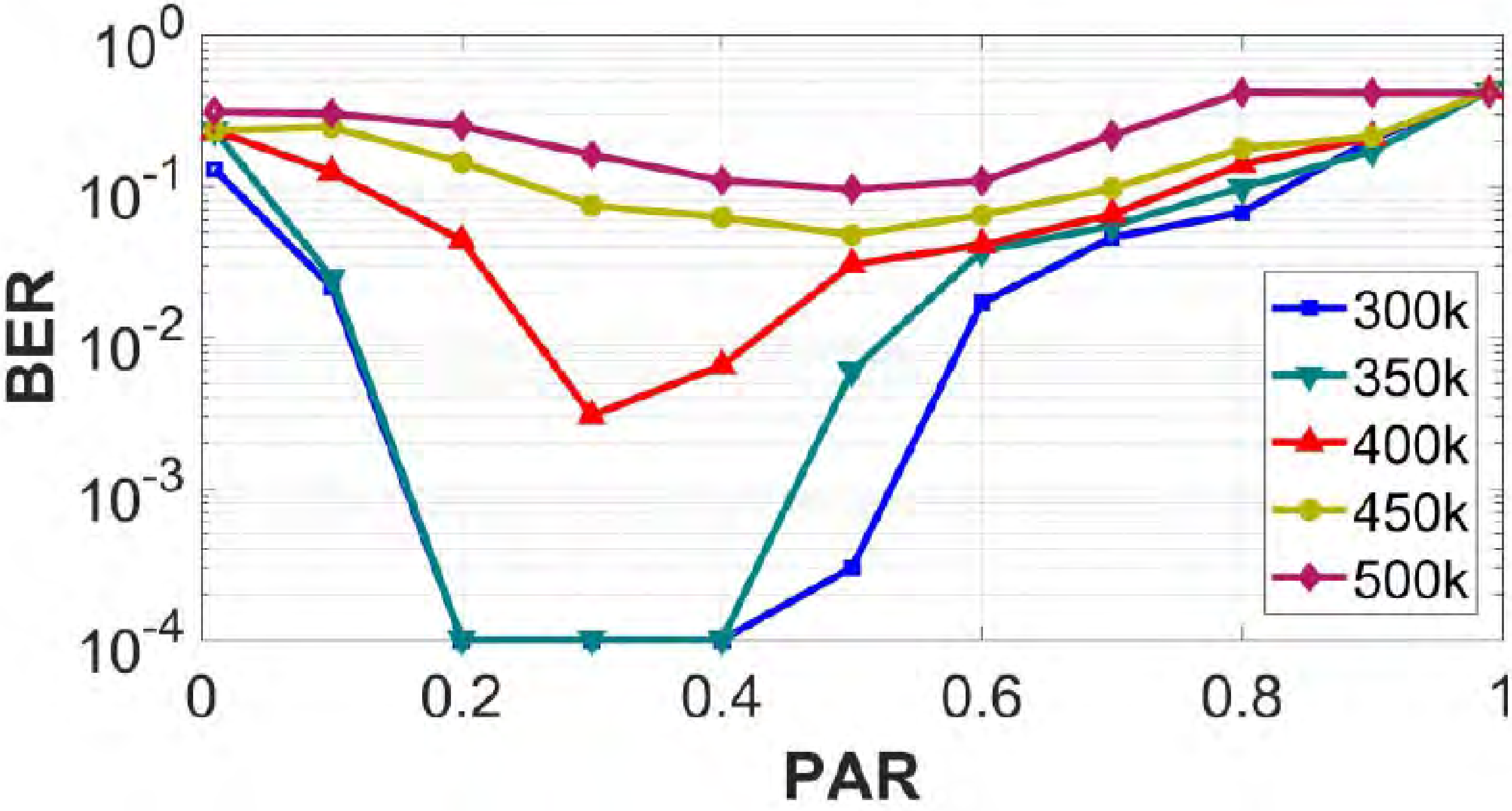
- **BER vs PAR.**



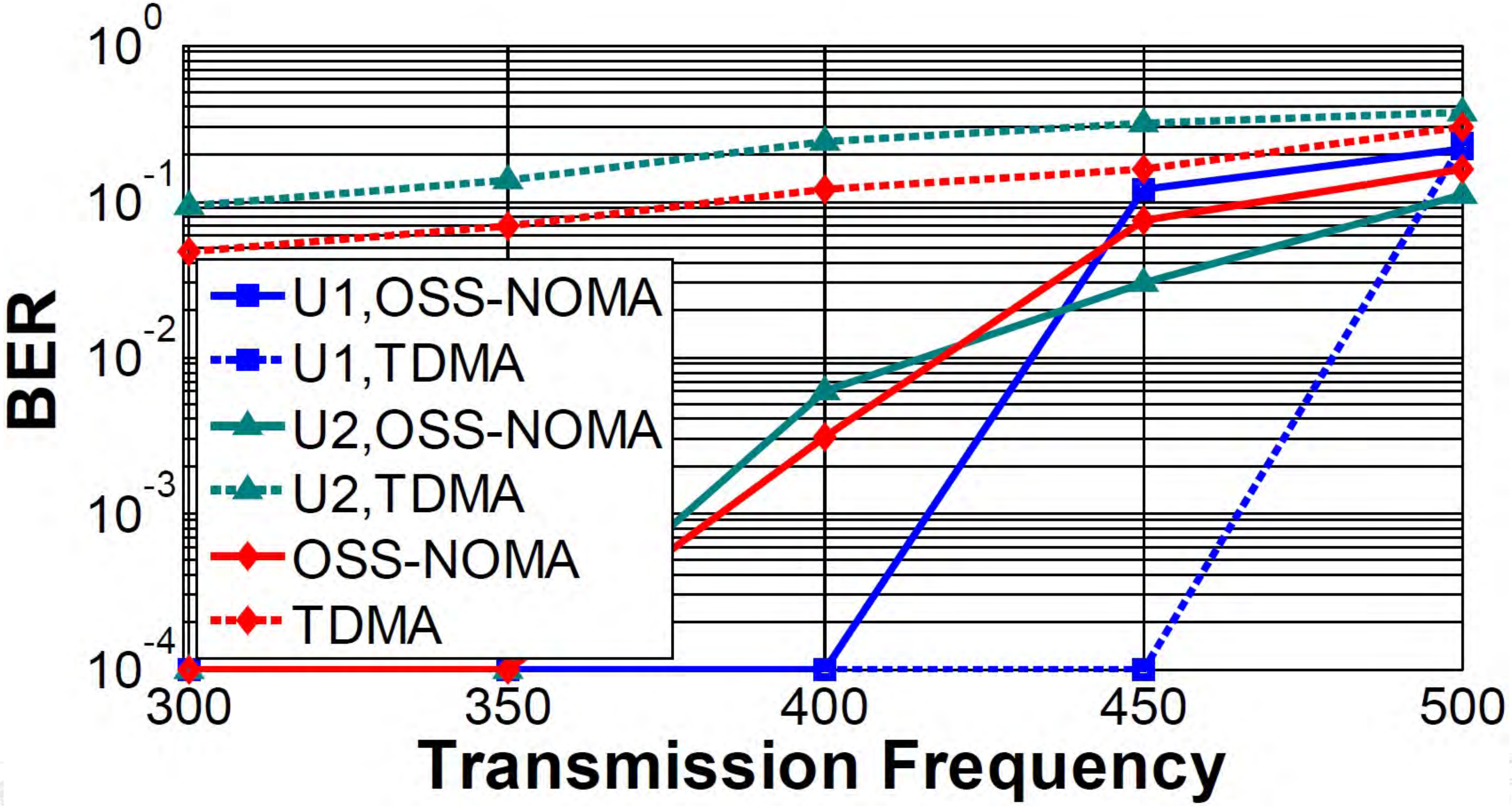
We position the near user (U1) and far user (U2) at distances of 40 and 100 cm from the transmitter,respectively.

NOMA VLC

- Average BER versus PAR at different T_f .



➢ **Performance comparison between the proposed OSS-NOMA and TDMA.**



We use pulse amplitude modulation (PAM4) for user1 and user2 in TDMA to achieve the same data rate as that delivered by OSS-NOMA with OOK.

- **A novel OSS-NOMA scheme has been proposed and implemented; it pushes the advanced NOMA technique into practical VLC systems.**
- **By leveraging the OSS technique, only digital control is required in OSS-NOMA VLC so as to avoid the negative affect of LED nonlinearity and complicated analog circuitry.**
- **Extensive evaluations show the prototype can deliver low average BERs of $\leq 3.1 \times 10^{-3}$ for two users at a data rate of 800 kbps, which strongly confirms its promising future for VLC-enabled IoT applications.**

谢谢聆听

敬请批评指正！