Visible Light Communications and Its Applications for 5G

Presented by:

OSA Optics in Digital Systems Technical Group

Optics in Digital Systems Technical Group

Introduction

Webinar: Visible Light Communications and Its Applications for 5G

28 February 2019

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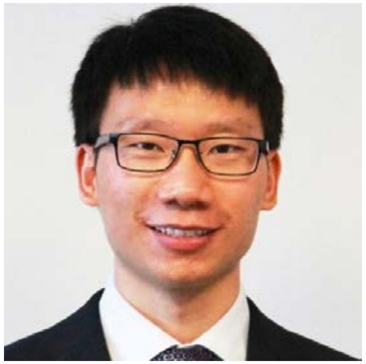

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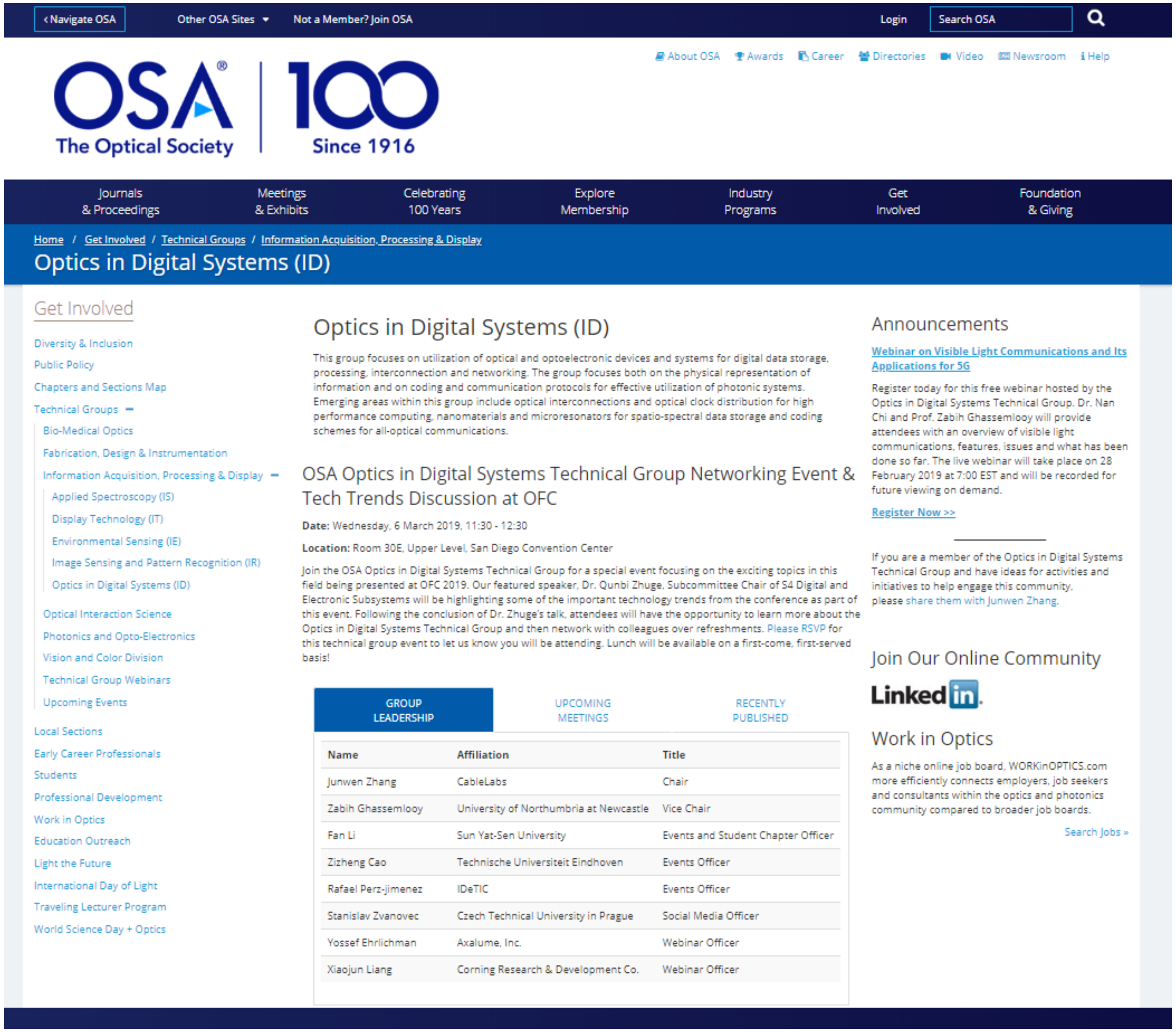
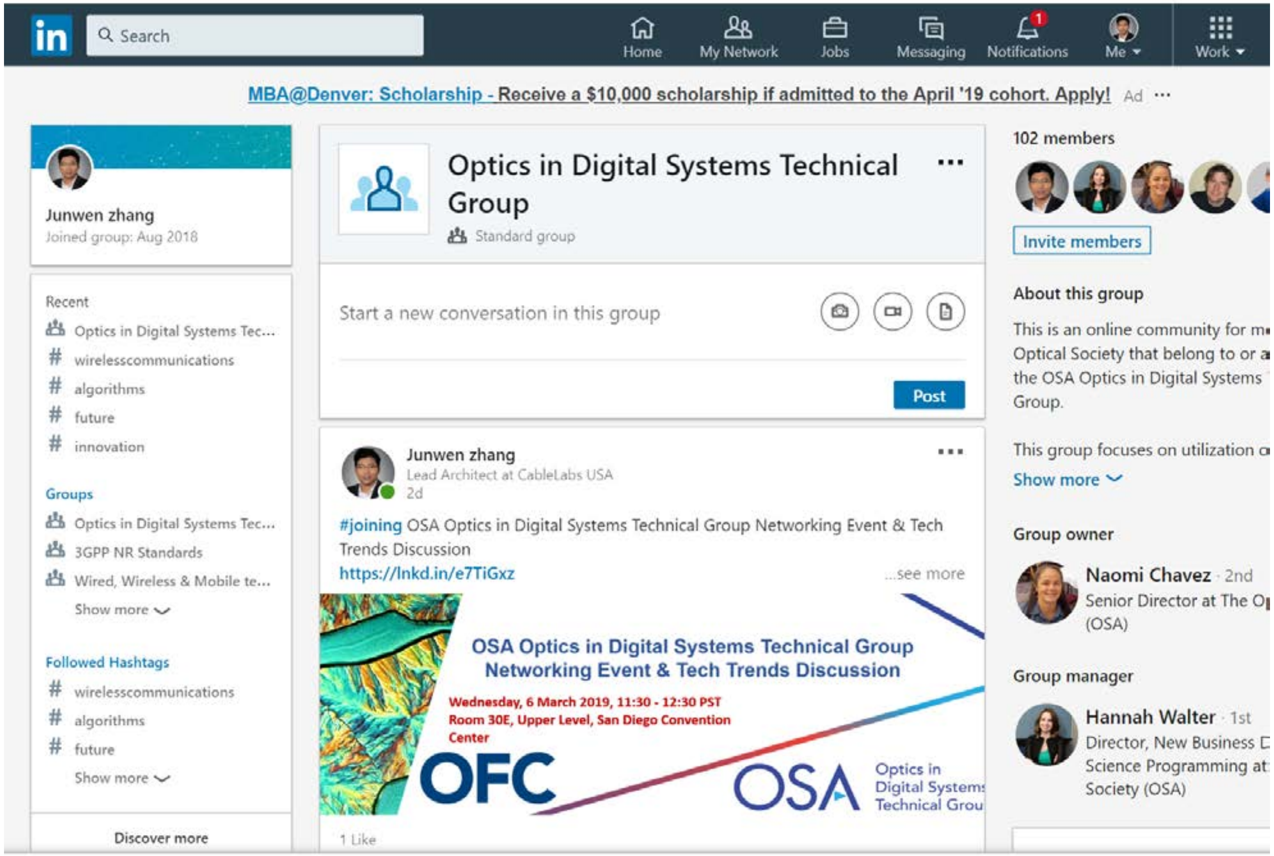


Contact Your Technical Group and Get Involved!

- LinkedIn group
- Announce new activities
- Promote interactions and engaging discussions



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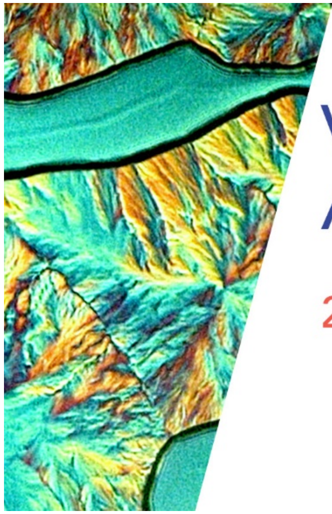
Welcome to Today's webinar!



VISIBLE LIGHT COMMUNICATIONS
AND ITS APPLICATIONS FOR 5G

28 February 2019 • 7:00 EST

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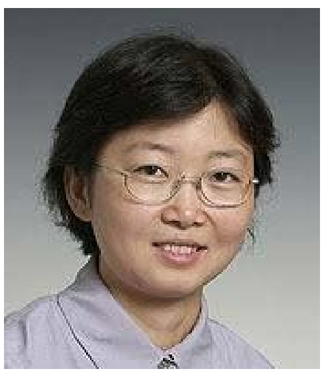

Prof. Nan Chi, Fudan University, China

Prof. Zabih (Fary) Ghassemlooy, Northumbria University, UK

OSA Technical Groups Webinar

Visible light communications and its applications for 5G

Fudan University

Nan Chi

电磁波信息科学重点实验室
Key lab of Electromagnetic Wave Information Science

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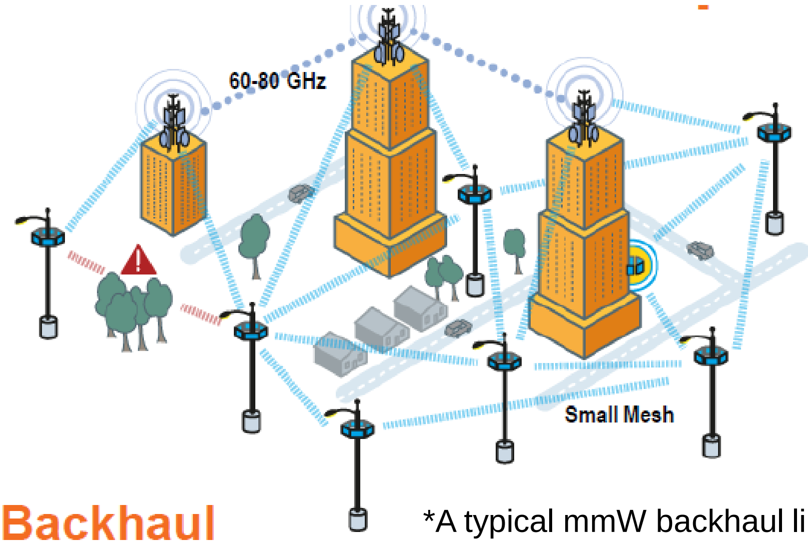
Outline

Background



Backhaul

*A typical mmW backhaul link

Backhaul is a top priority for small cell deployments
•80% of small cells will have wireless backhaul
•Cost of fiber is ~4x greater than wireless (cumulative CAPEX/OPEX)
•Small Cell mesh inter-connectivity over ~250m
•Large indoor and outdoor public spaces

** According to InterDigital Whitepaper 2013*

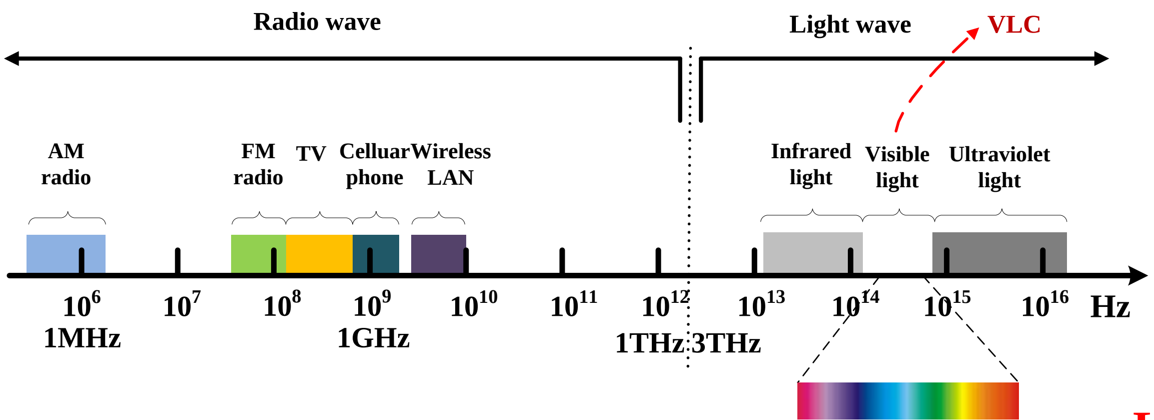
VLC outdoor free-space high speed communication for mobile backhaul

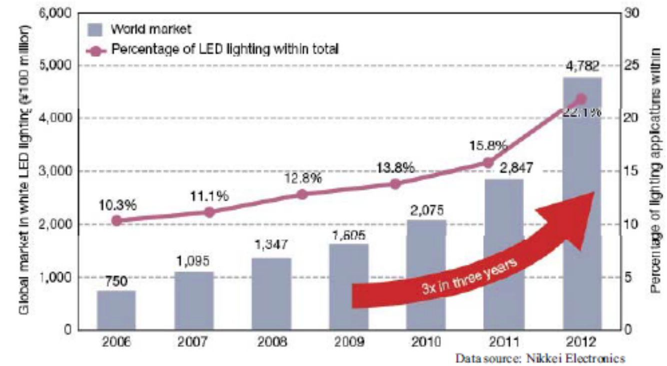
- It shares the same CAPEX/OPEX advantages with mmW
- More competitive with lower device cost

Characters:

- Large indoor/**outdoor public spaces**
- Distance: **~50 m~1 km**
- Speed: **~Gbps**
- Link: **mainly Point-to-point**

Research Motivation of VLC





LED lighting in the global market

- **Expand the spectrum for the next generation of broadband communications**
- **Combine lighting with communication, bringing unique advantages**

By 2018, the semiconductor lighting penetration is 80%. With the popularity of LED lighting process, VLC will be standing on the shoulders of giants.

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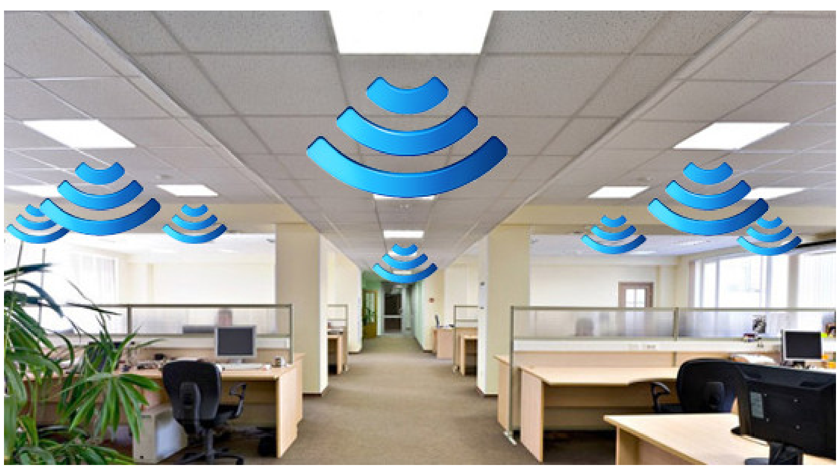
Application Scenarios

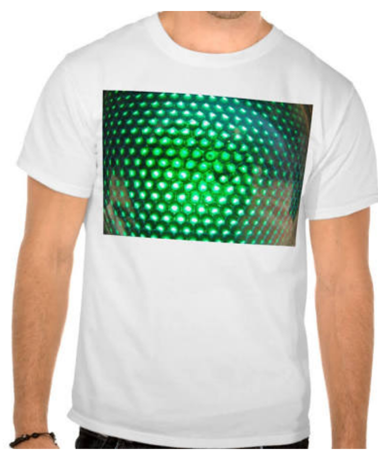
Street Light Hot spot

V2V Light Communication

Indoor Communication&Navigation



Wearable LED Communication



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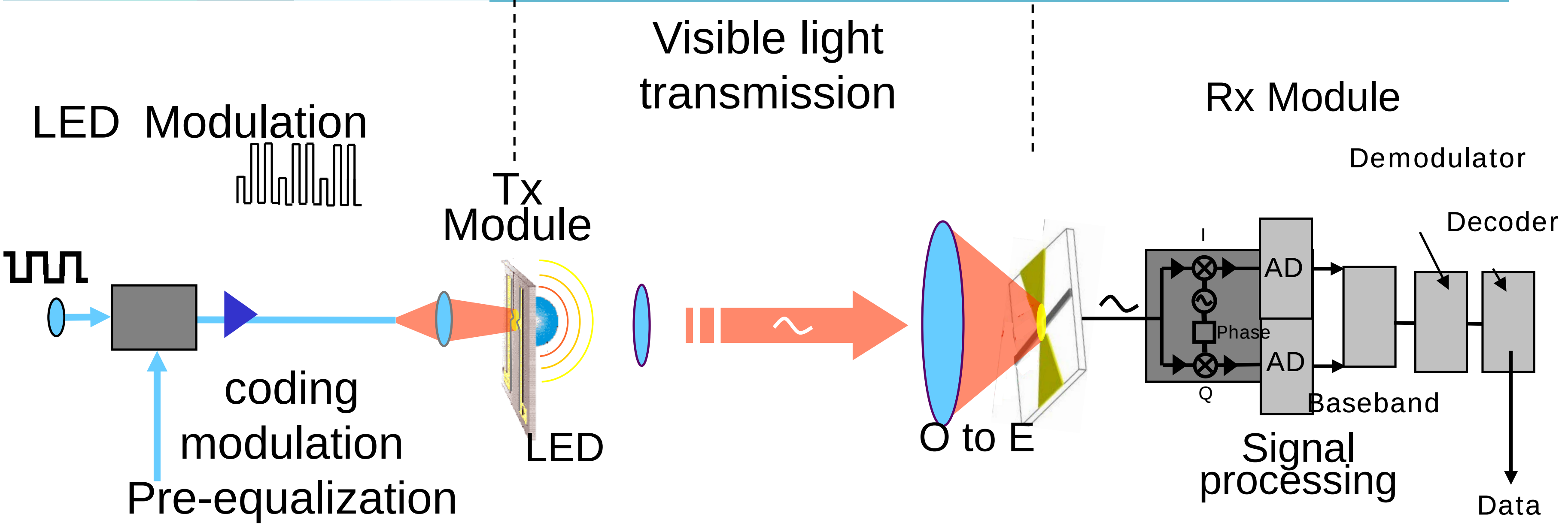
Research Motivation of VLC

	Carrier frequency	Bandwidth	Rate
VLC	400-800THz	400M/1G	10Gb/s (Single LED)
WIFI	2.4GHz, 5GHz	20M/40M	1Gb/s
4G/5G	1.9GHZ-3.8GHZ	20MHZ	1Gb/s

1. The white light is safe for human eyes
2. No electromagnetic interference, applications in the electromagnetic-sensitive environment (airplane, hospital, etc)
3. Energy conservation because of providing with functions of illumination, communication and control positioning
4. Spectrum license free
5. Suitable for security communication

Schematics of VLC system



- **TX:**
  - electronics: LED driving circuit, signal processing (coding, modulation, equalization)
  - optics: transmitter antenna
- **RX:**
  - optics: receiver antenna, PD
  - electronics: signal processing (decoding, demodulation, equalization)

The research directions

LED visible light communication

material/chip

- LED
- SLD
- LD
- Detector array
- Organic LED and metamaterial

High speed system

- modulation
- Pre-equalization
- Post-equalization

Multiplexing/ network

- WDM/PDM
- MIMO
- VLC+PON network
- LED LiFi network
- Seamless integration with ULEAPS fiber

New approaches

- Underwater
- Machine learning

1 Material/chip

2 High speed system

3 Multiplexing/networking

4 Underwater VLC

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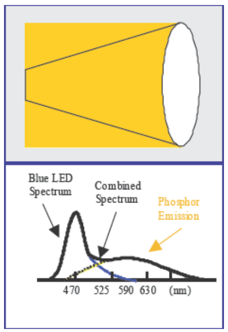
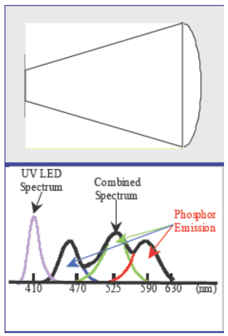
Various LED/SLD/LD transmitter

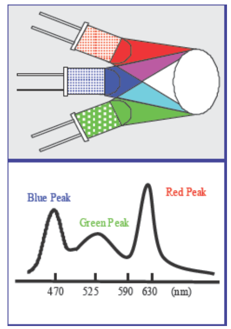
Blue LED
+
Yellow phosphor



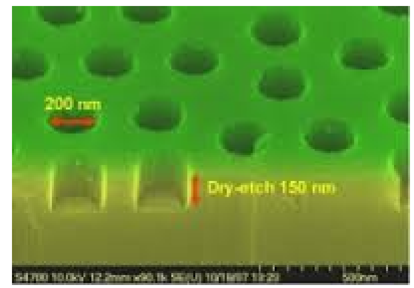
UV LED
+
RGB phosphor



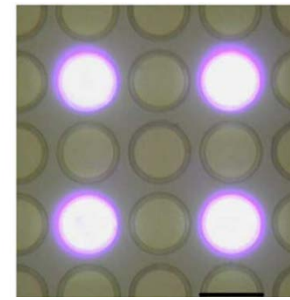
RGB LED



Photonic crystal LED



Micro-LED



LD and SLD courtesy by Chao Shen KAUST

- **LED:** spontaneous emission, droop effect, less than 100MHz 3dB bandwidth
- **SLD:** amplified spontaneous emission, no droop effect, 3dB bandwidth 400MHz ~800MHz
- **LD:** stimulated emission, no droop effect, 3dB bandwidth GHz

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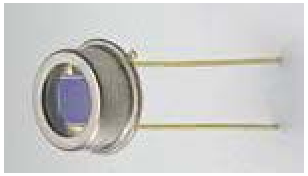
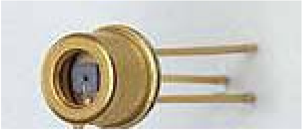
Different receivers





- PIN photo diode

  high speed reception up to 1Gbps

- Avalanche photo diode

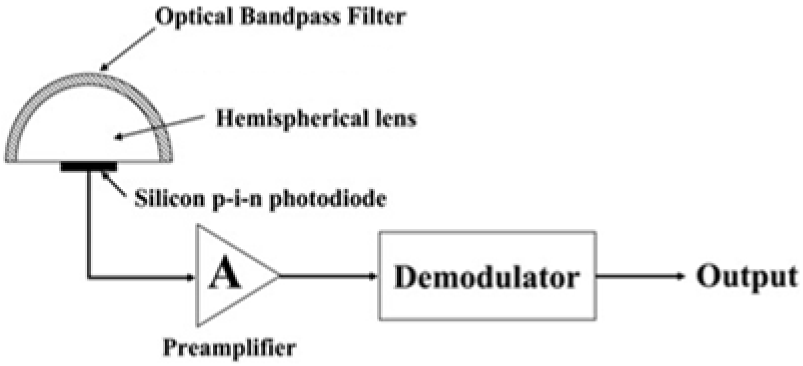
  higher receiver sensitivity

- Image sensor

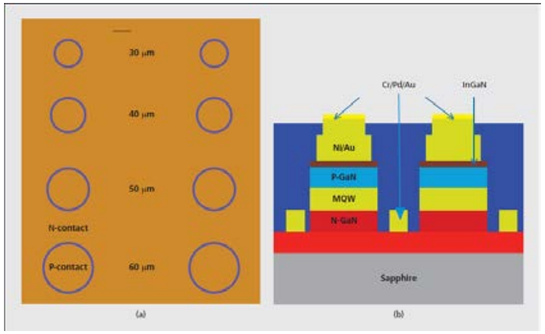
  simultaneous image acquisition and data reception

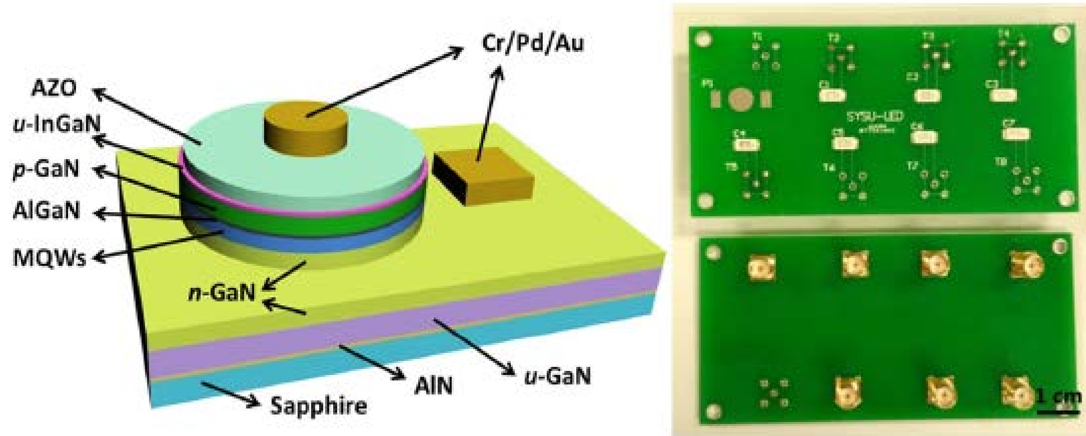
- Filter & Lens

  increase the data rate



High-bandwidth micro-LED chip





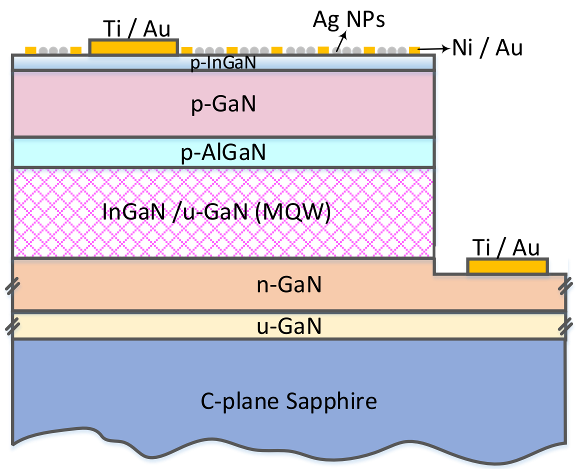
(a) (b)

- A μLED array device with hybrid pixel sizes from 30 ~60 μm is designed and fabricated.
- Depositing 250nm-thick Al-doped ZnO layer epitaxially on conventional LED epi-stacks through MOCVD
- 600MHz modulation bandwidth without pre-equalization
- 3Gb/s for a single channel(more higher speed can be expected based on the SNR=20.89dB)

Z Sun, et al, IEEE Photonics Journal 8 (3), 1-8

LED Based on Surface Plasmons

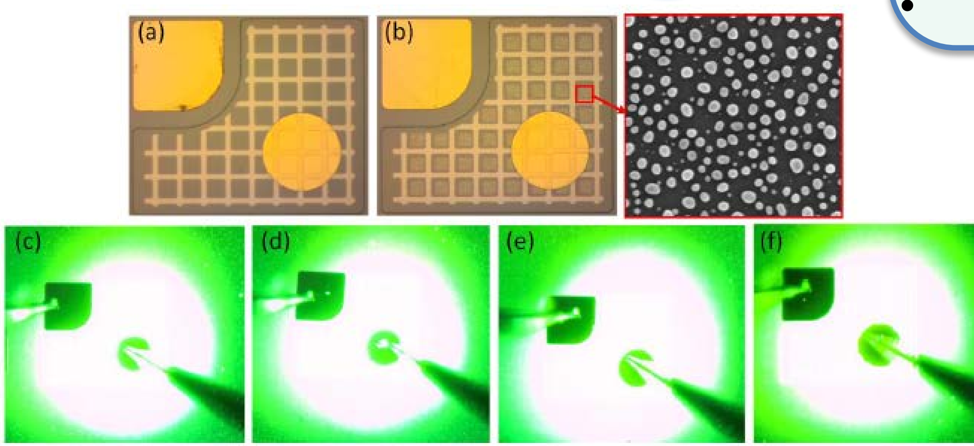
❑ SP LED fabrication——collaboration with DTU



- Epitaxial: Commercial green GaN-LED
- Device size:

	mesa size	p-contact	p-pad	n-contact
LED device	200μm	190μm	65μm	85μm

- p-contact: Ni/Au
- p-pad & n-contact: Ti/Au
- Voltage: about 3V



Sample	f_{3dB} (MHz)
Grid LED	72.92 (1)
SP-LED A	96.67 (1.33)
SP-LED B	201.13 (2.75)
SP-LED C	81.54 (1.12)

- SPs increase the carrier spontaneous emission rate, due to the new energy transition channel of electron-hole pairs in LEDs created by the quantum-well (QW)-SP coupling.

A Fadil, H Ou, N Chi CLEO: Science and Innovations, STu3R. 2

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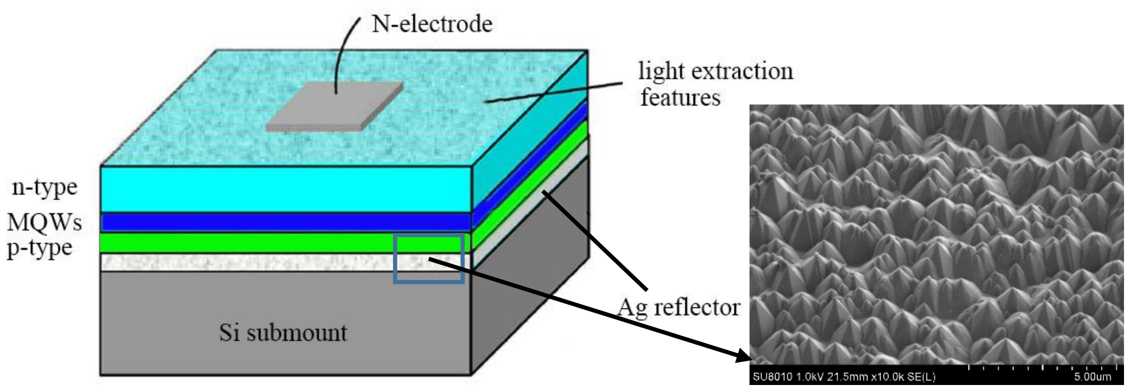
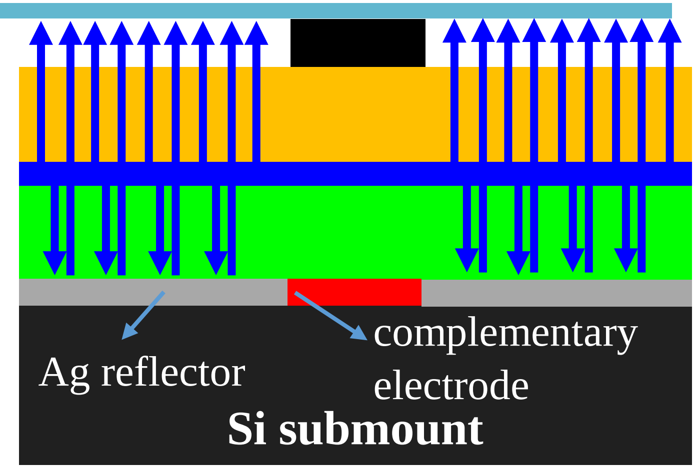
Si-based LED-Increasing light extraction efficiency





➢ Vertical structure LED

- single side luminescence
- better light-emitting uniformity
- better in direction

➢ Complementary electrode

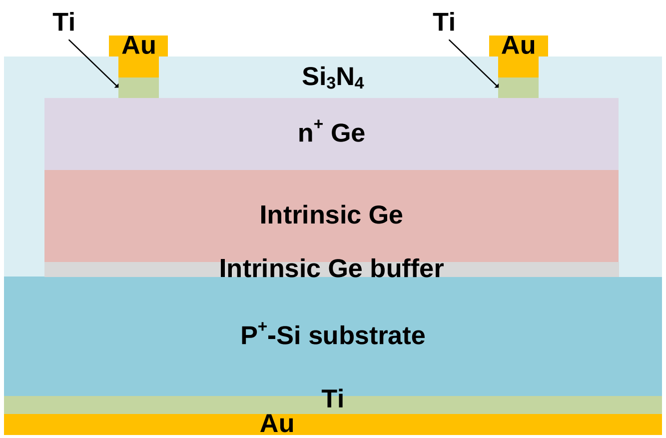
- reduce light absorption by electrode
- improve current spreading

➢ Ag reflector

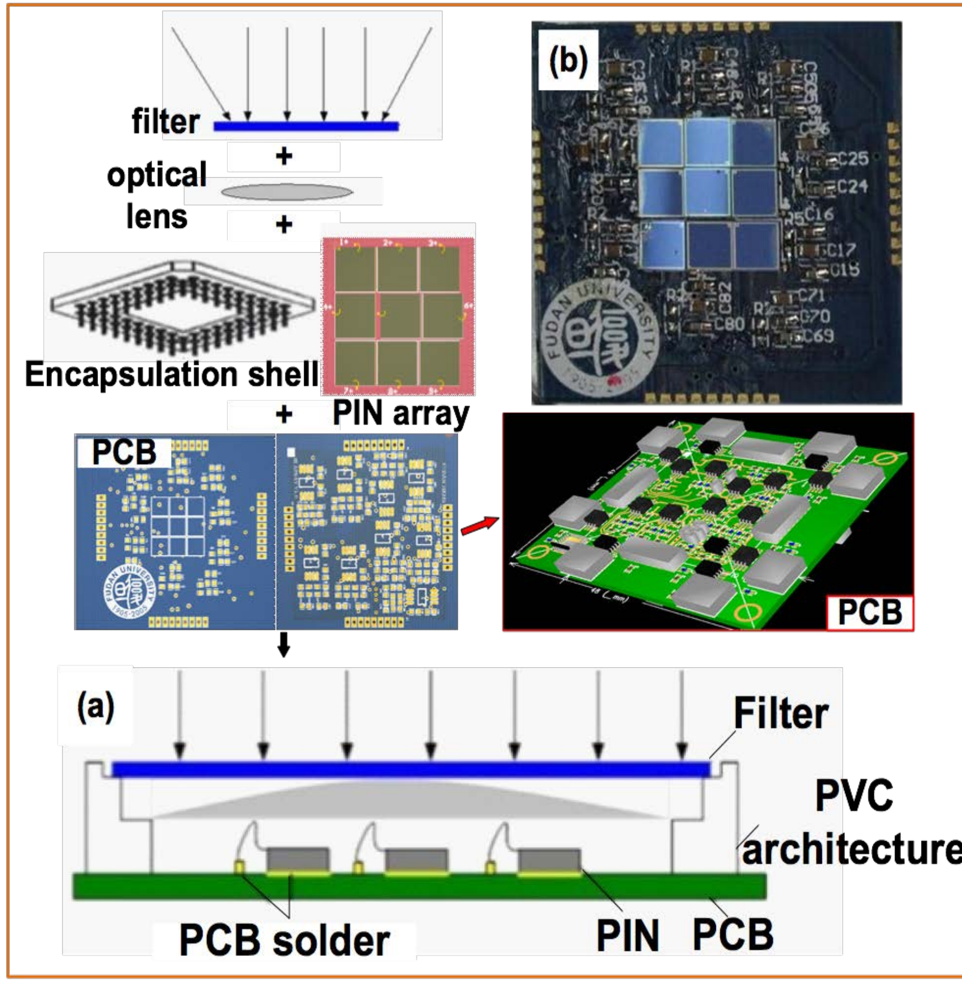
- alleviate light absorption of Si-submount

☐ Hemispherical and pyramidal pattern surface textured GaN based vertical LED is to increase in light extraction efficiency ,Ag reflector is used to improve single side luminescence , and complementary electrode is to increase single side luminescence area.

Fabrication of Integrated PIN array

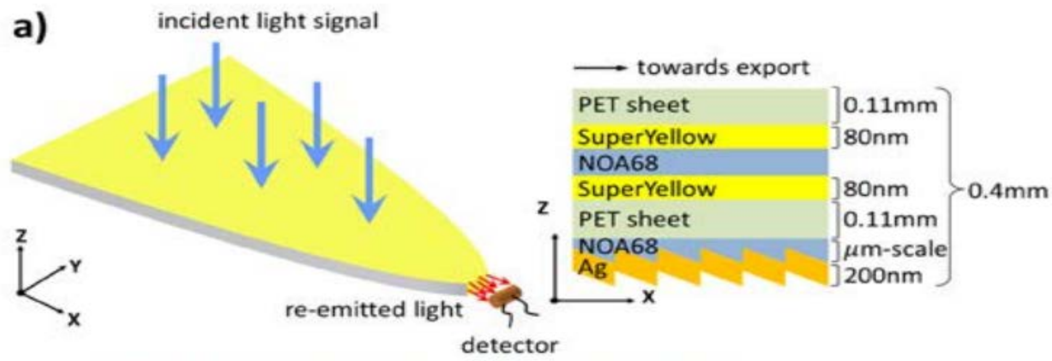


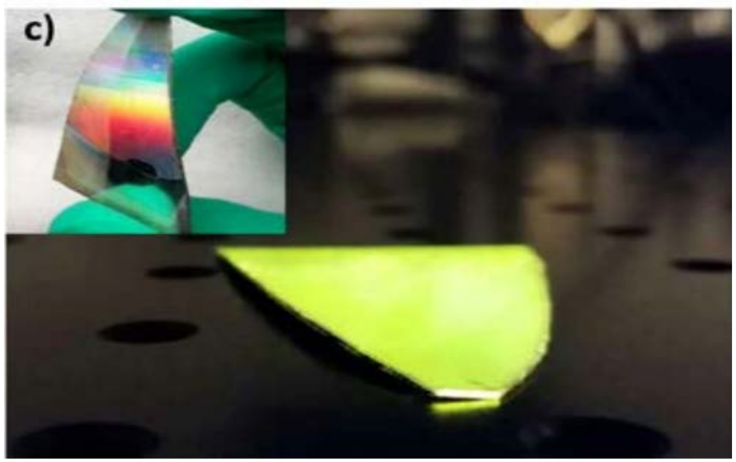
- 3x3 PIN array
- Bandwidth of single PIN: 25MHz
- PIN unit：3mmx3mm
- PIN array: the size less than 5cmx5cm



[1] J.H. Li, *et al.*. An integrated PIN-array receiver for visible light communication, Journal of Optics, 17(2015), 105805.
[2] J.H. Li, *et al.*. A 2x2 imaging MIMO system based on LED Visible Light Communications employing space balanced coding and integrated PIN array reception, OpticsCommunications, 367(2016), 214–218.

Nanopatterned luminescent concentrators for visible light communications



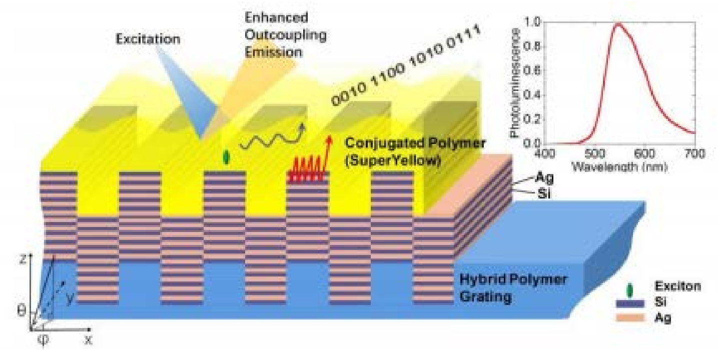


Experimental Results

- A data rate of 400 Mb/s for nanopatterned CPC shape LSCs is successfully achieved in 0.5-m indoor free space transmission;
- The data-rate can only reach 250 Mb/s when the same illuminated area of photodiode was directly excited by the blue LED, since the received SNR can only support a 4QAM OFDM;
- A 60% improvement in the data-rate can be achieved using nanopatterned CPC-shape LSCs.

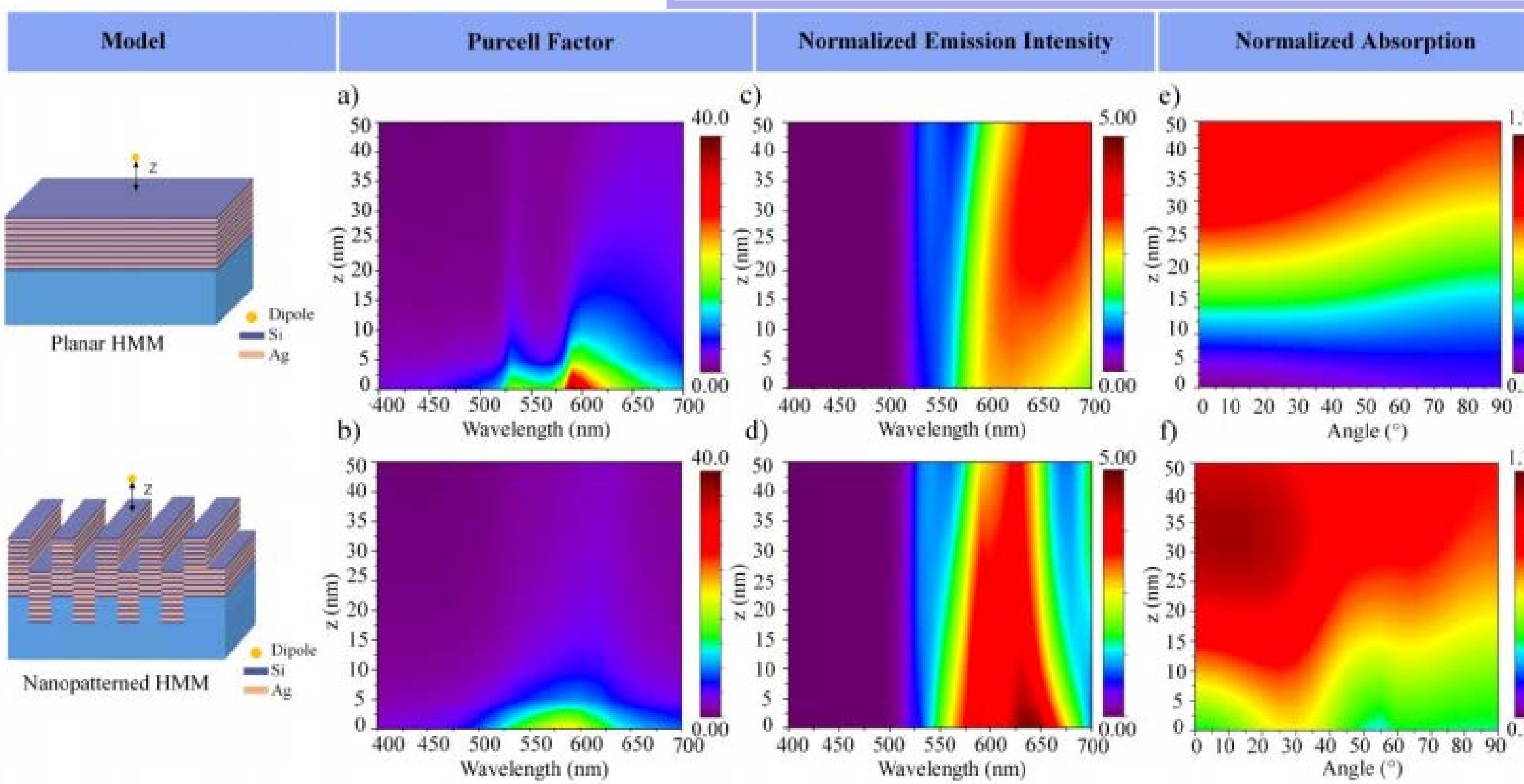
Dong Y, Shi M, Yang X, et al., *Opt. Express* 25(18), 21926-21934 (2017).

Enhancing Communication Bandwidths of Organic Color Converters Using Nanopatterned Hyperbolic Metamaterials



Design

- 1Dimention binary Bragg grating on the substrate of hybrid polymer
- The grating has a period of 190nm, a groove depth of 30nm and a filling factor of 50%.
- A 67% improvement in bandwidth, datarate 150 Mb/s



Yang X, Shi M, Yu Y, et al., *Journal of Lightwave Technology*, 2793217 (2018).

1 Material/chip

2 High speed system

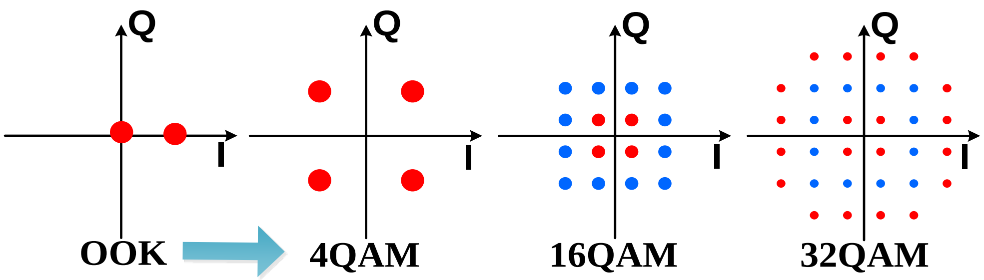
3 Multiplexing/networking

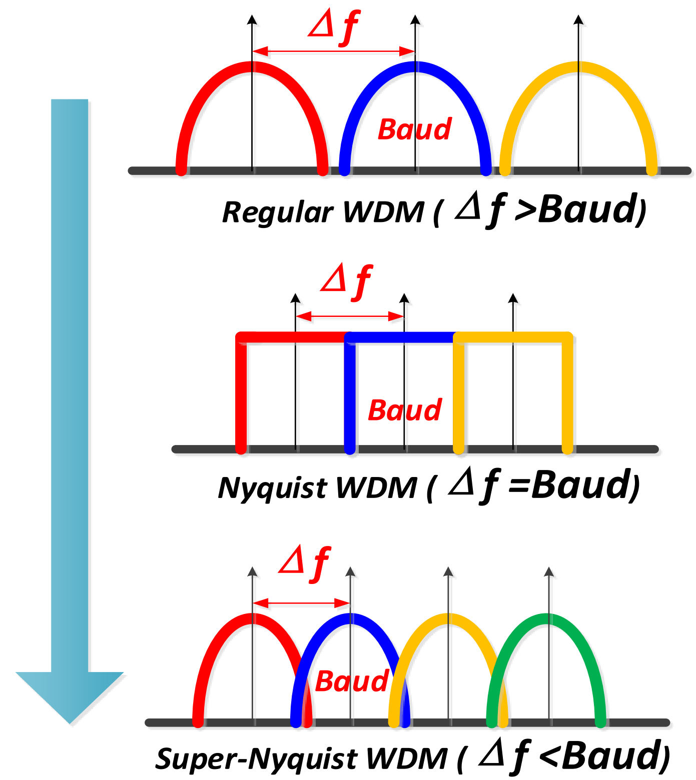
4 Underwater VLC

How to achieve high speed and high spectrum efficiency

$$\mathbf{E}(t) = \sqrt{P(t)}\cos\left[\omega_0(t)\,t - \phi(t)\right]\hat{\mathbf{x}}(t)$$

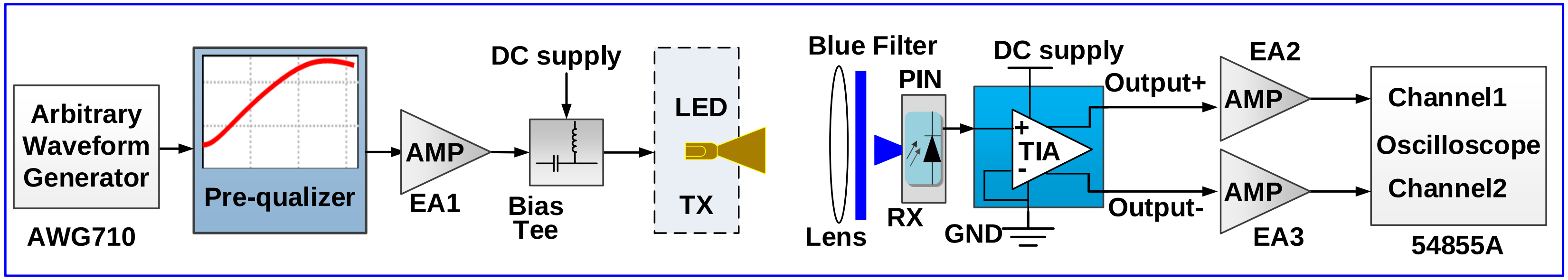
Amplitude	Frequency	phase	polarization
OOK	FSK, MSK	DPSK, QPSK	PolSK, OAM

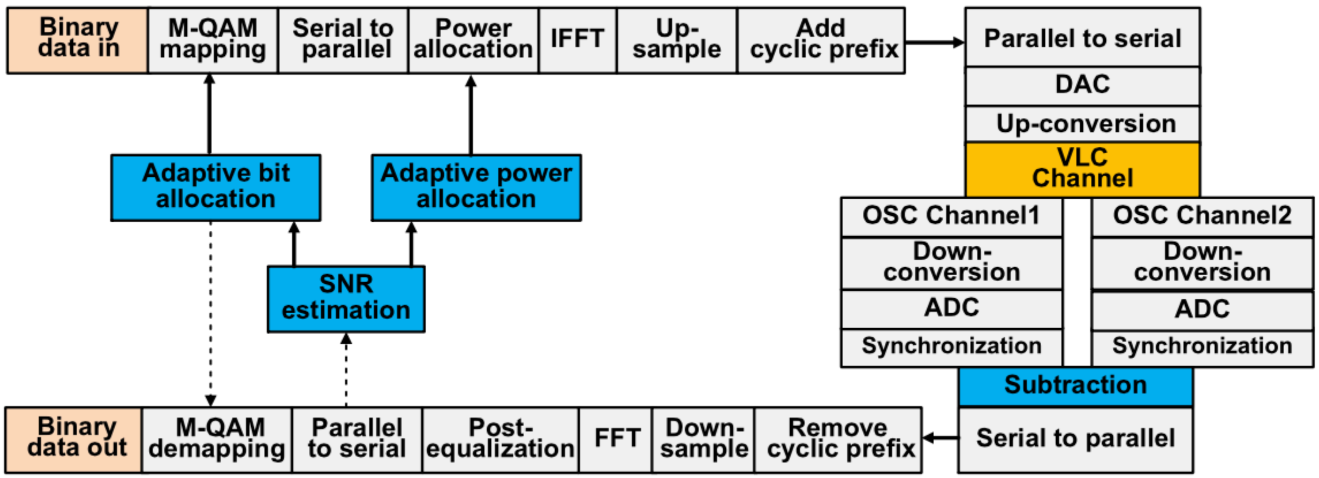




- From one-dimensional modulation to multi-dimensional modulation;
- From on-off keying modulation to multi-level modulation;
- From Nyquist modulation to super-nyquist modulation;

2.28 Gbit/s bit-loading OFDM VLC system



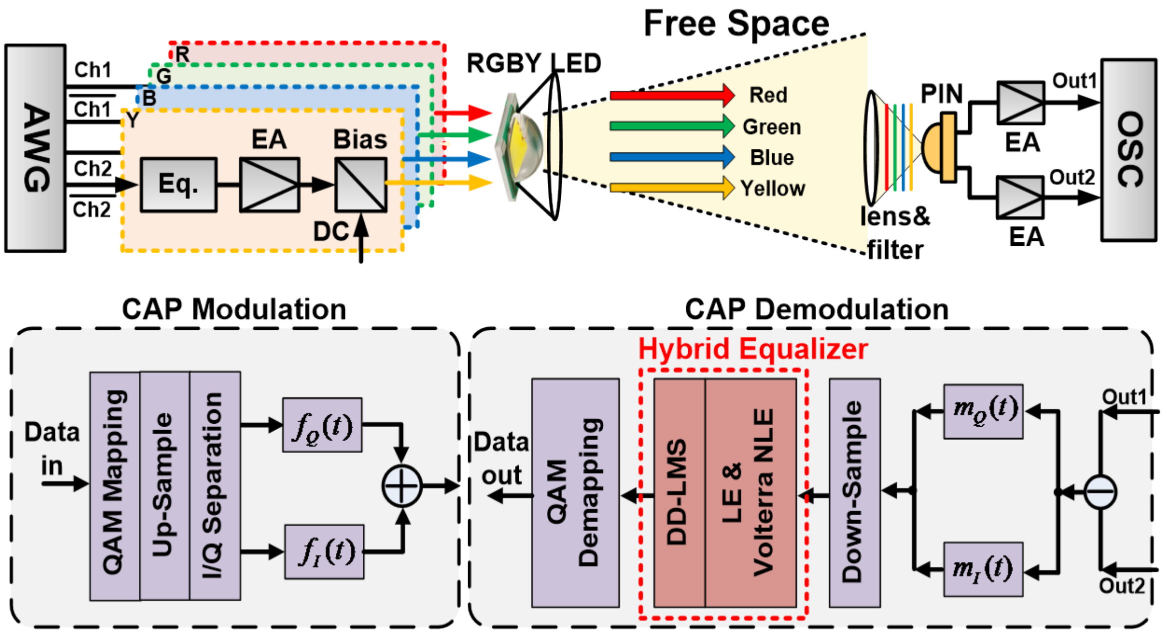


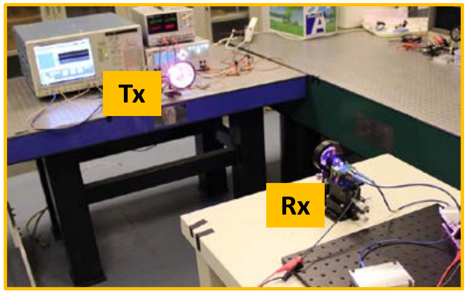
- transmitter: phosphorescent white LED
- Single pre-equalizer: f_0 = 368.0MHz
- Differential receiver: PIN
- Transmission length: 1.5m-3m

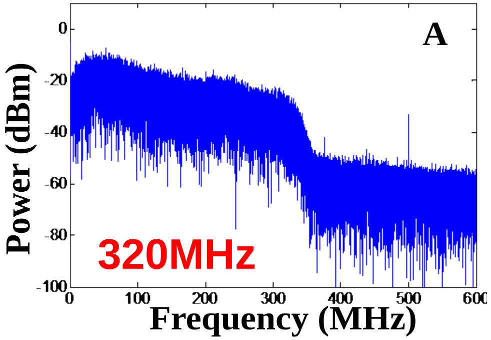
- Modulation format: bit-loading OFDM
- Subcarrier No.: 256
- Overhead: 3% CP, 9% Training
- Bandwidth: 600MHz(520.8 MHz)

Xingxing Huang, et al. . Photonics Journal, IEEE, 2015, 7(5): 1-8.(SCI)

8Gb/s CAP VLC system





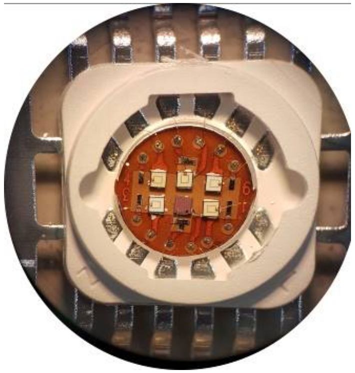


Experimental setup

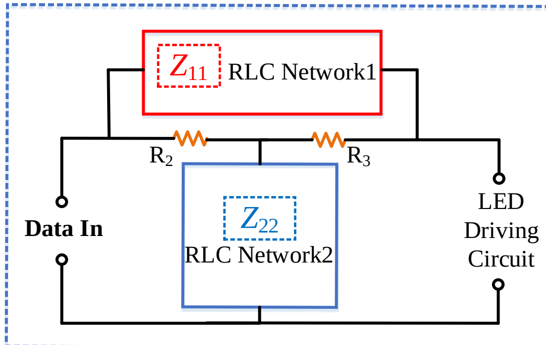
- RGBY LED is utilized for 4 wavelengths multiplexing;
- Passive pre-emphasis circuits, bandwidth can be improved from 25MHz to 320MHz
- A reflection cup with 60º divergence angle is applied;
- A differential receiving circuit is designed to increase the SNR;

Y. Wang, et al, IEEE Photonics Journal, 2015

10.7Gb/s DMT VLC system using a silicon LED

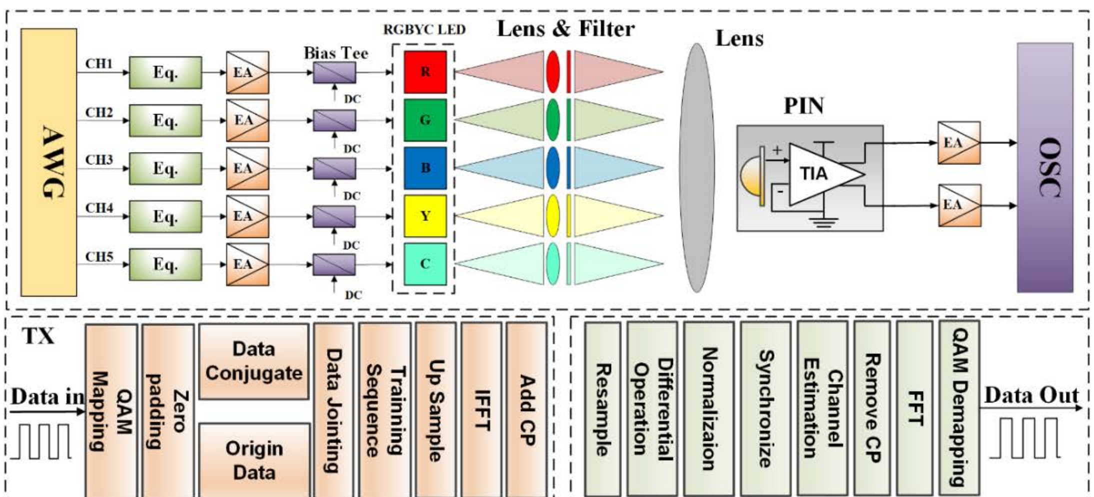


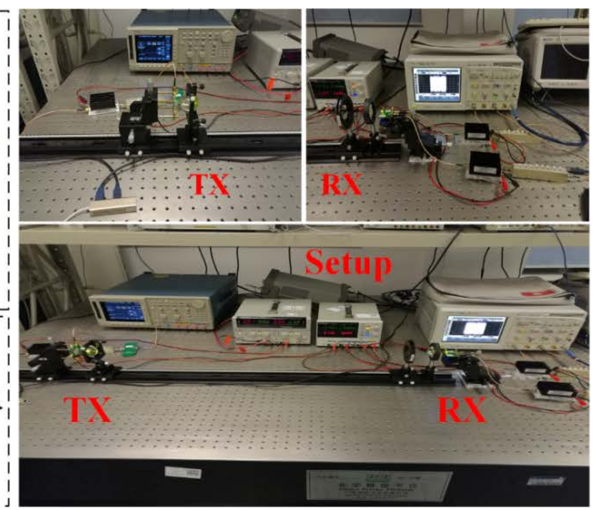
RGBCY CM- LED



Bridged-T
Pre-equazlier

- Si-Based RGBYC LED
- 64QAM-DMT
- Transmission distance: 1.2m
- data rate of RGBYC 2.175Gb 2.25Gb, 2.175Gb, 1.8Gb, 2.325Gb respectively





F. Wang, et al, OFC 2018

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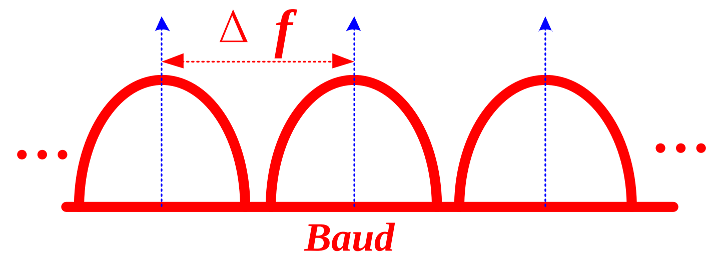
Super-Nyquist WDM (Faster-than-Nyquist)

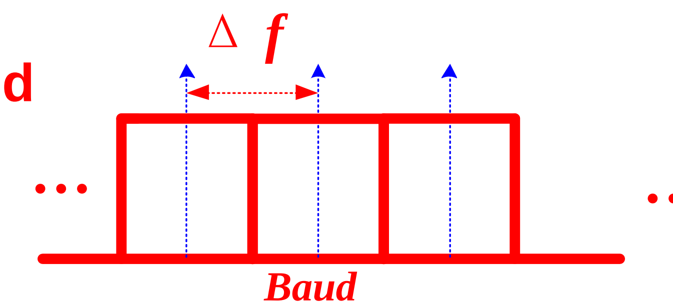
1995

- **WDM: Carrier spacing Δf >Baud**
- Guard-bands between channels
- Negligible crosstalk & no ISI
- Lowest SE



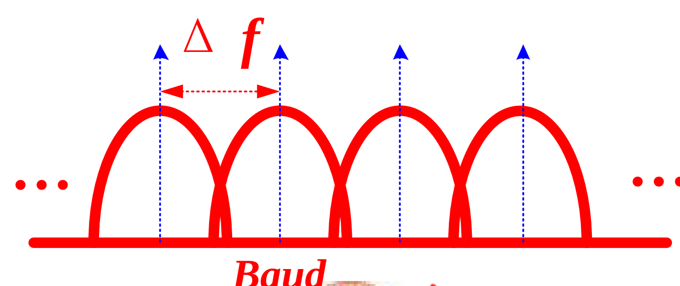
2008

- **Nyquist-WDM: Carrier spacing Δf =Baud**
- No Guard-band
- Zero Crosstalk & zero ISI
- Higher SE



2010

- **Super-Nyquist WDM: Carrier spacing Δf <Baud**
- Highest SE
- Introduced Crosstalk & ISI
- Additional DSP (Multi-Symbol detection)



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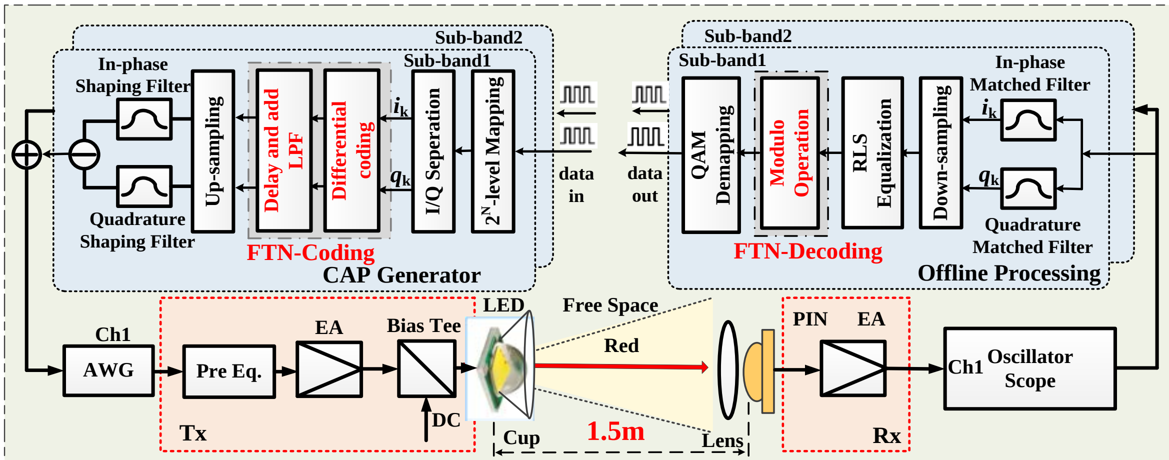
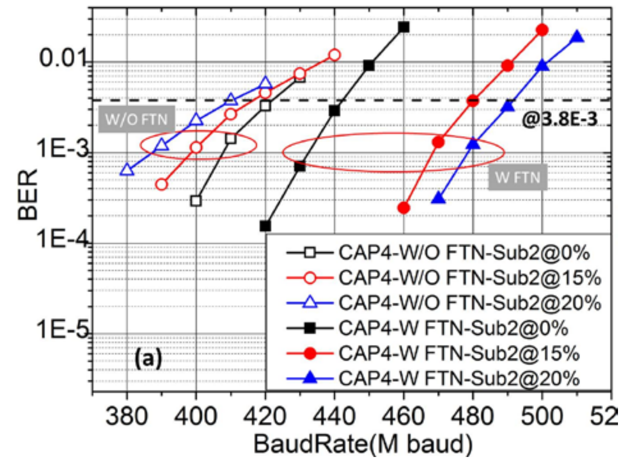
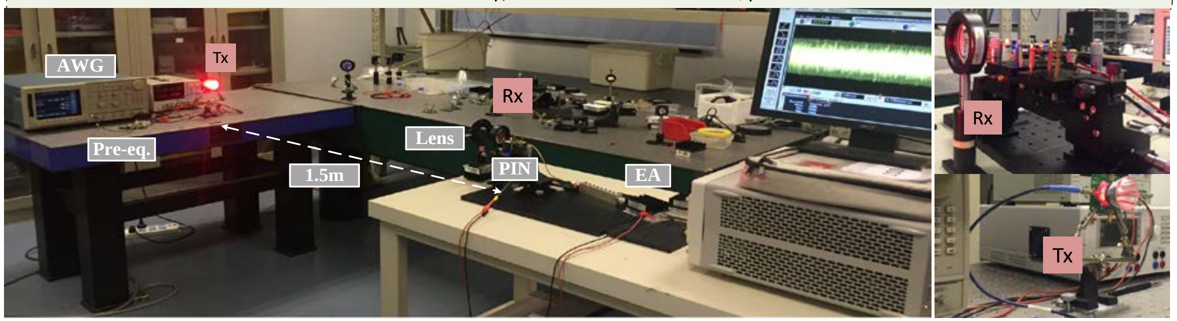
Faster-than-Nyquist CAP







- Red LED chip, bandwidth after pre-equalization 350MHz
- Data rate 1.47Gbps, transmission length 1.5m
- FTN can successfully save the modulation bandwidth up to 20%.

N. Chi et al, Chinece Optics Letters, 2017

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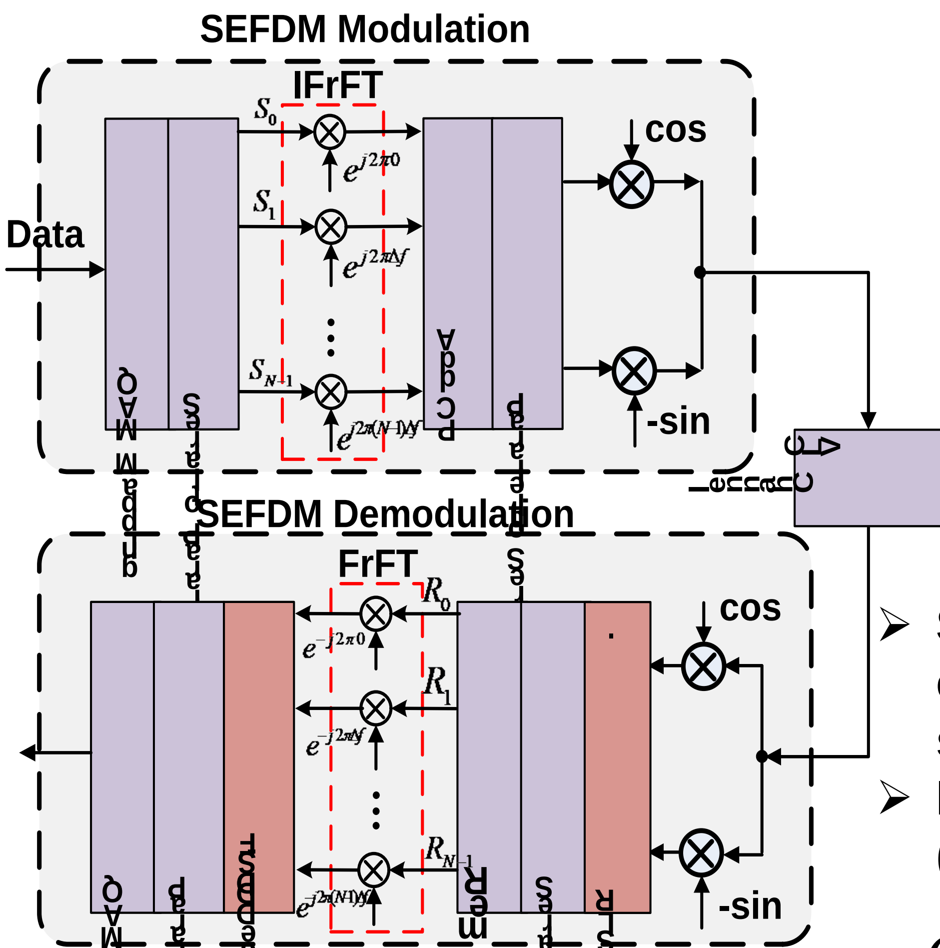
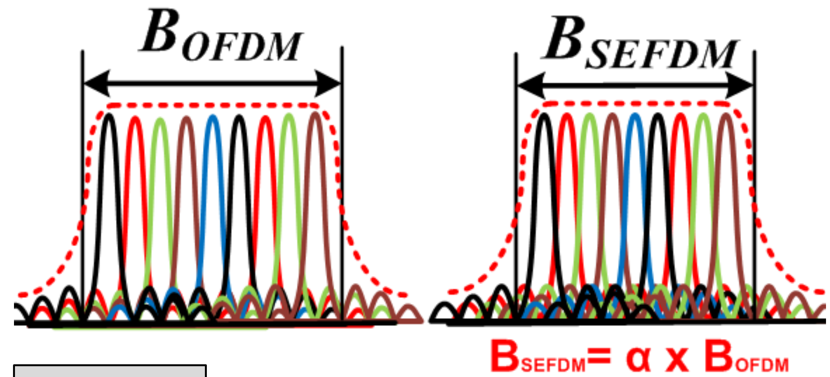
SEFDM Based Spectrum Compressed VLC System



Y. Wang et al, ECOC 2016



IFrFT:

$$x(t) = \frac{1}{\sqrt{T}} \sum_{l=-\infty}^{\infty} \sum_{n=0}^{N-1} s_{l,n} \exp\left[\frac{j2\pi n\alpha(t-lT)}{T}\right]$$

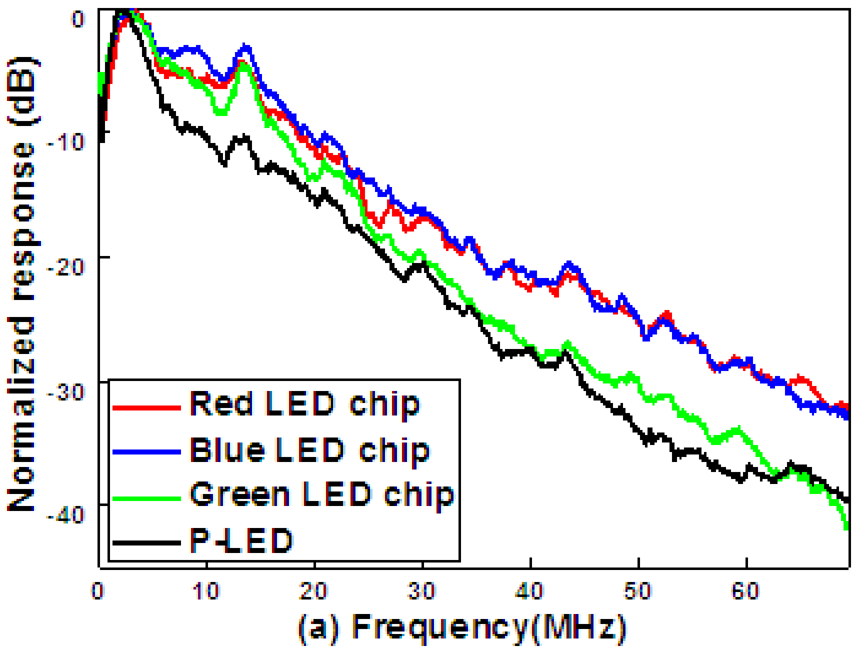
- **Spectrally efficient FDM (SEFDM) employs non-orthogonal overlapped subcarriers to compress spectrum.**
- **Inverse fractional Fourier transform (IFrFT) is utilized for SEFDM modulation**

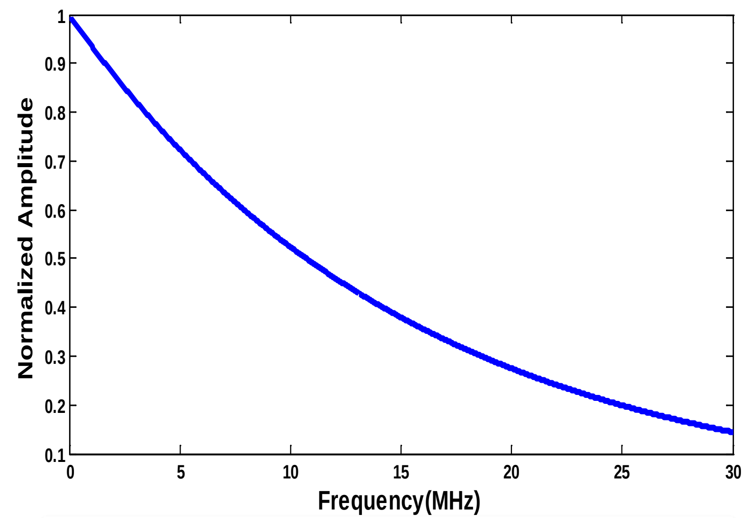
$\alpha = \Delta f \cdot T$ **Is the Compression Factor**

- **For the first time we introduce SEFDM in the bandwidth-limited VLC system.**

Y. Wang et al, IEEE PJ 2016

LED Channel Model





The fitting channel response

- Blue phosphor LED 10dB bandwidth is around 15MHz
- RGB LED 10dB bandwidth is around 25MHz
- Large attenuation at high frequency

Narrow bandwidth & Nonlinearity

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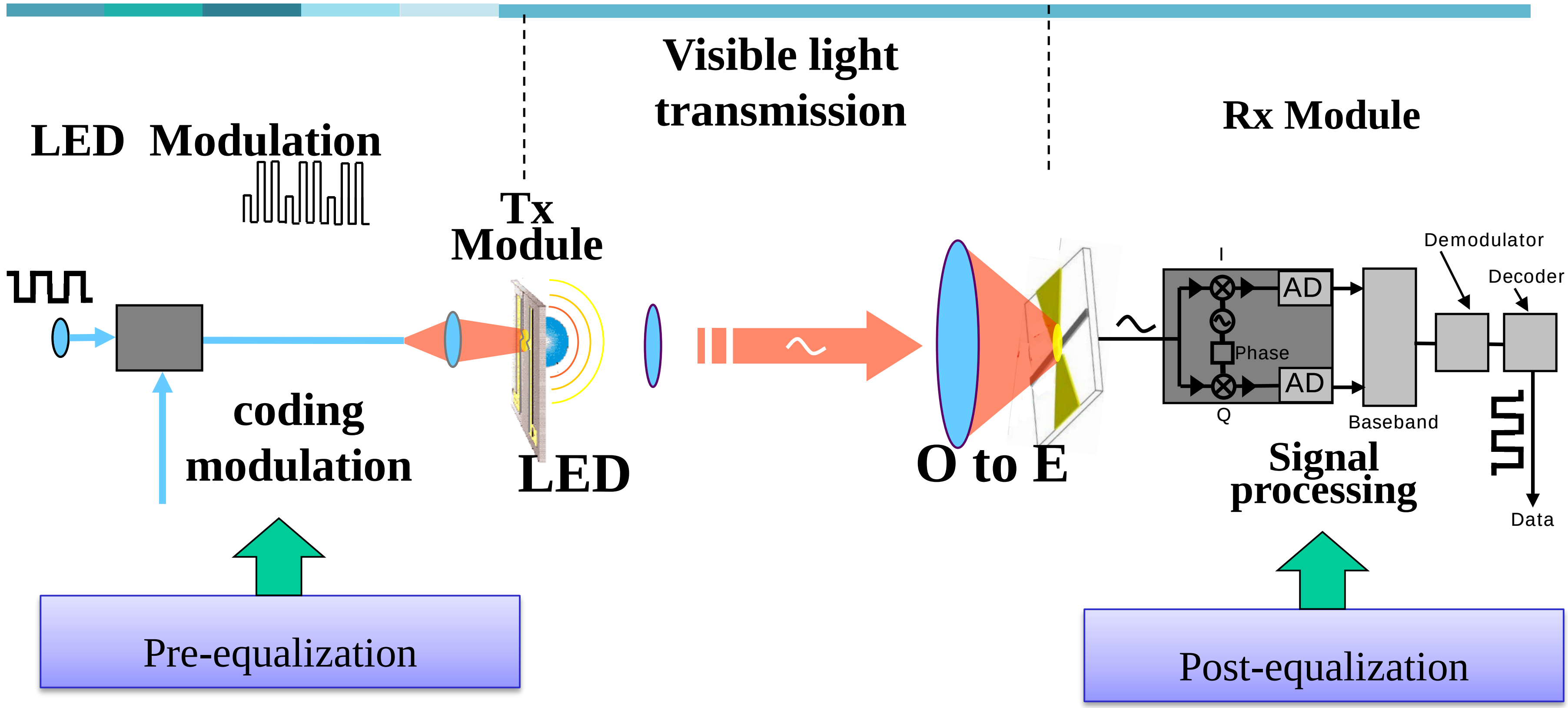
VLC Channel Pre-/Post- equalization

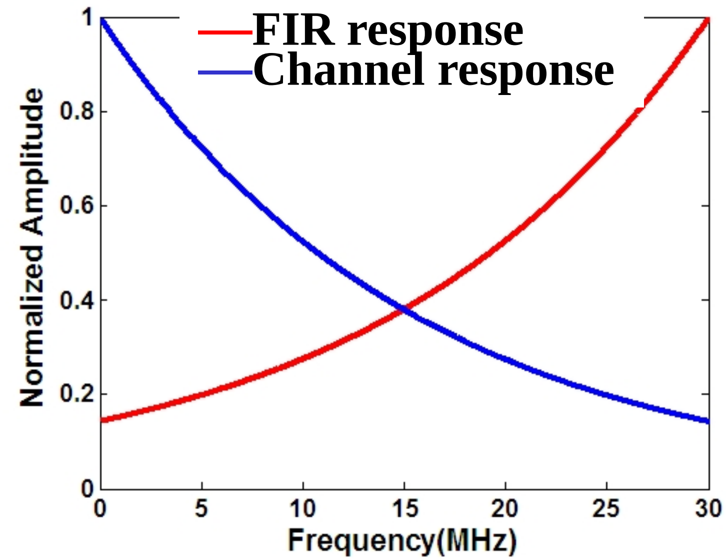


- Pre-equalization schemes:
  - Hardware Equalization： RC hardware circuit design
  - Software Equalization： Advanced digital signal processing

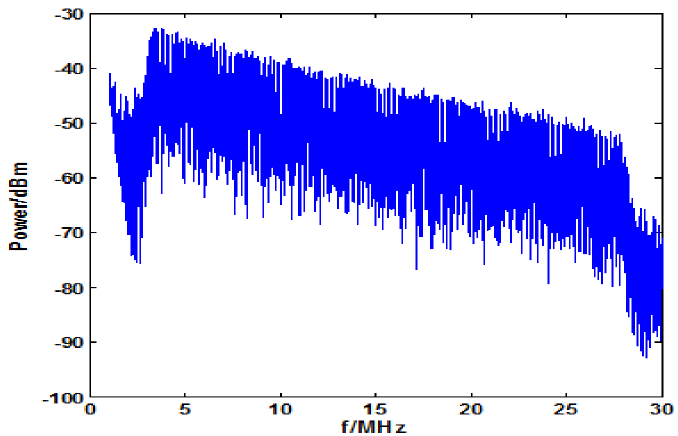
Software Pre-equalization

Pre-equalization

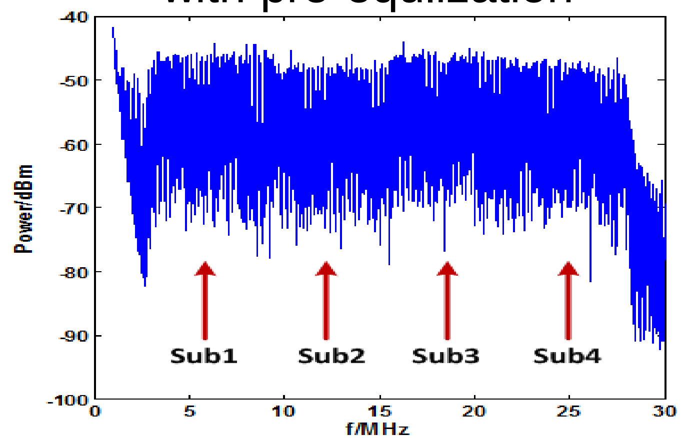
- ✓ Obtain the channel knowledge(H) at the RF domain
- ✓ Make pre-equalization Tx*1/H at the baseband



w/o pre-equlization



with pre-equlization



Y. Wang, et al, IEEE Communication Letters, Vol. 18, No. 10

Y. Zhou, et al, Mathematical Problems in Engineering, 2016

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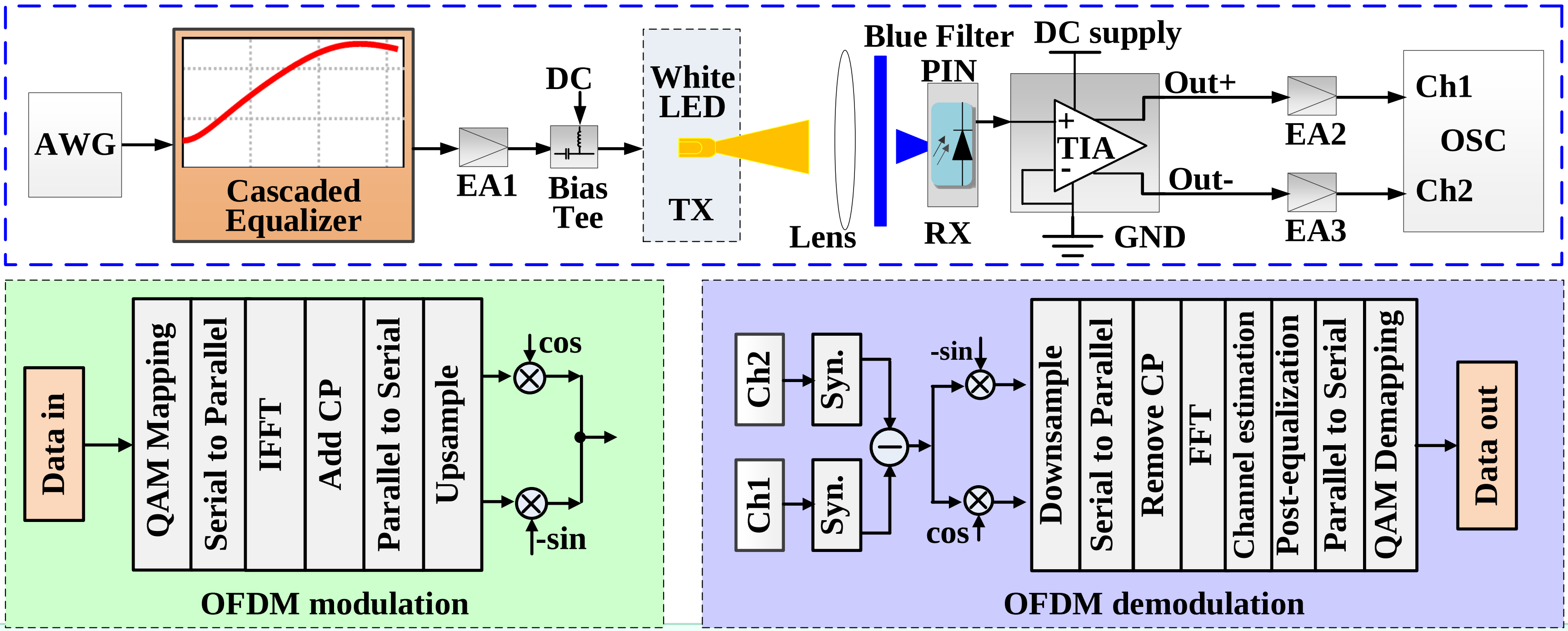
1.6 Gbit/s phosphorescent white LED and cascaded equalizer

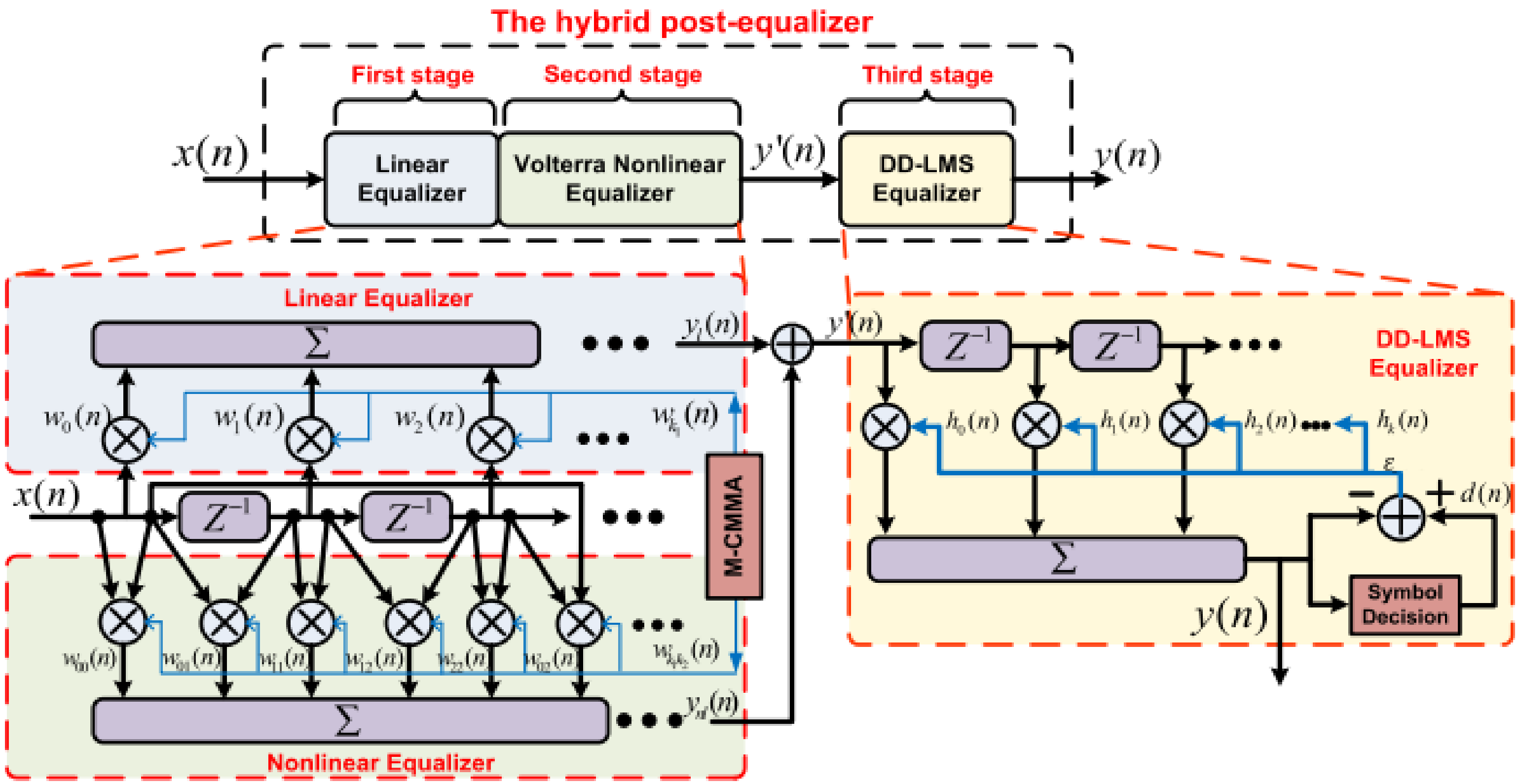


- The cascaded equalizer is used in the data transmission experiment because of its wider bandwidth.
- Transmitter: Phosphorescent white LED, AWG (Tektronix AWG710), subcarrier number = 128, up-sampling factor = 4
- Receiver: Lens, TIA, EAs, differential outputs PIN receiver

Xingxing Huang, et al, IEEE Photon. Technol. Lett. , 2015.

X. Huang, et al, Optics express, 2015

CAP VLC system with hybrid post equalizer



Principle

- The first stage filter is a **linear equalizer** based on **M-CMMA** which is a blind multi-modulus;
- A **Volterra series** based **nonlinear equalizer** is applied as the second stage filter
- Third stage filter uses DD-LMS to update the weights of equalizer.

Nan. Chi, et al, Journal of Lightwave Technology, 2017

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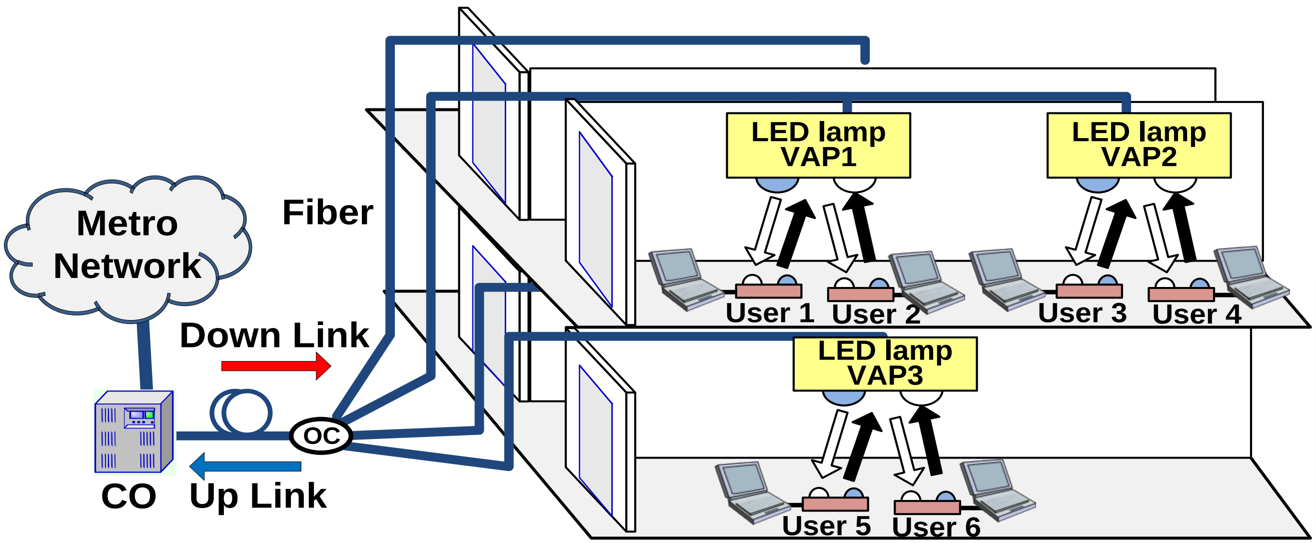
1 Material/chip

2 High speed system

3 **Multiplexing/networking**

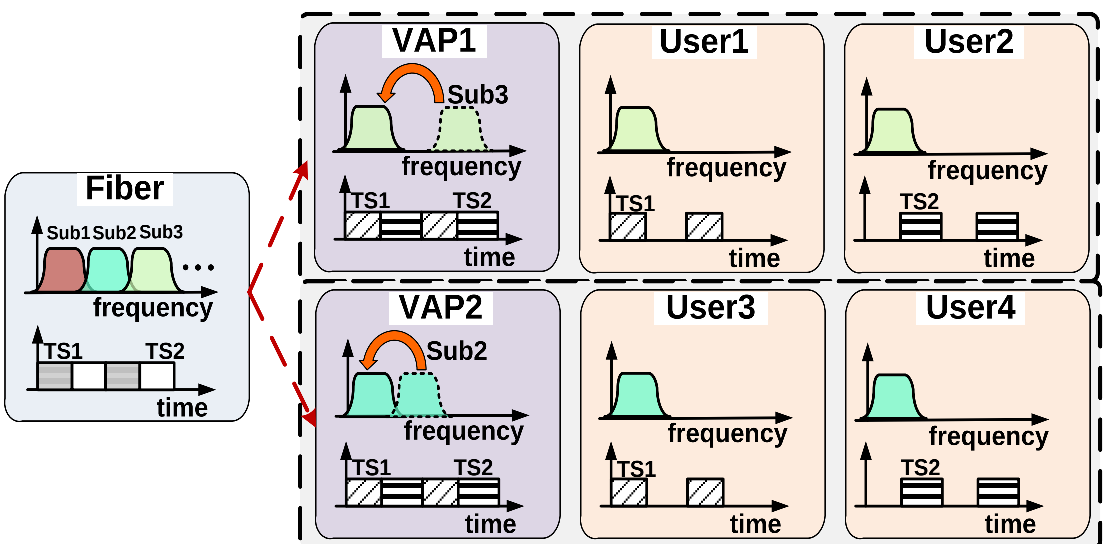
4 Underwater VLC

VLC-Fiber integrated local area access network



How to realize VLC wireless access for massive users

1. High capacity of optical fiber;
2. OFDM: Dynamic subcarrier allocation

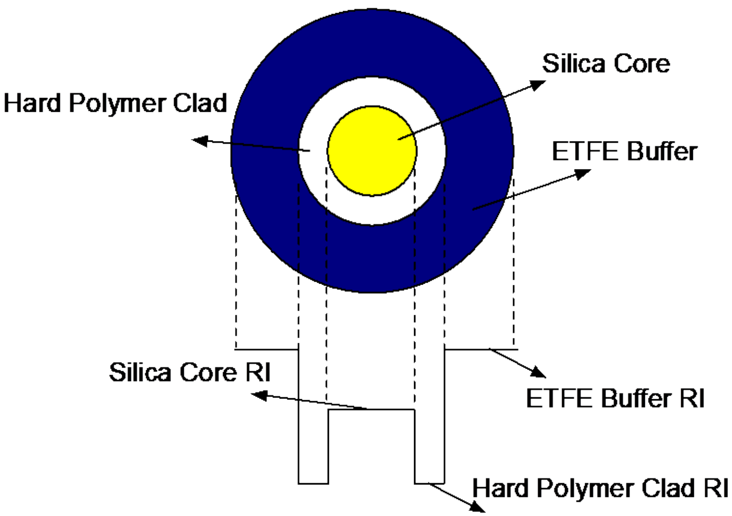


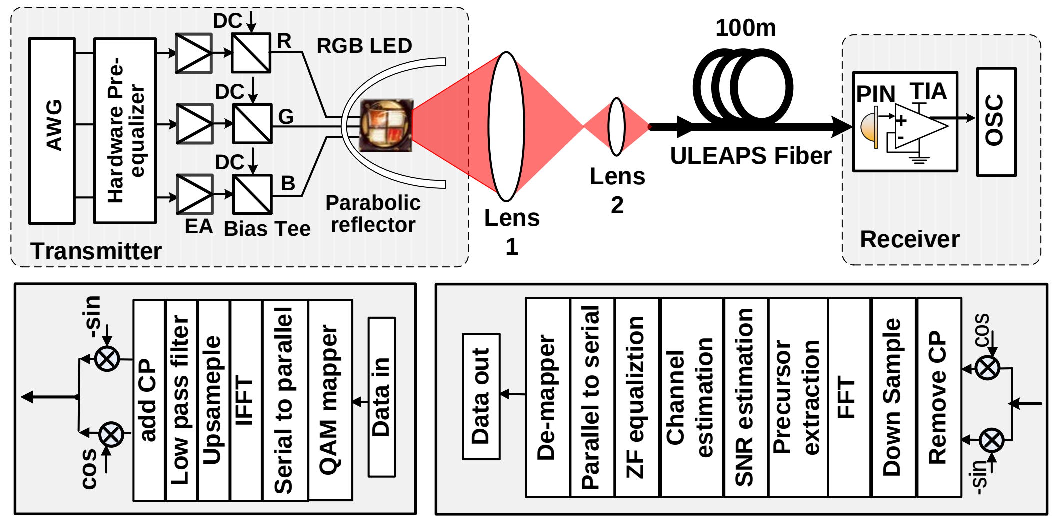
Multi-user access

- Optical Fiber is used as the network backbone;
- Star topology network architecture;
- FDM for each VAP;
- TDM for each user;

Y. Wang, et al, IEEE Photonics Technology Letters, 27(2), Issue 99, 2014. (**SCI**)

VLC over Fiber Transmission System





VLC

- The numerical aperture of this fiber is 0.37±0.02 and the attenuation @850nm is 8.0-dB/km
- 5-m ULEAPS fiber, data rate 3.1-Gb/s；
- 100-m fiber, data rate 2-Gb/s；
- 16QAM-OFDM modulation；
- Red LED and silicon PIN

Shi J , et al., MOTL, 2018

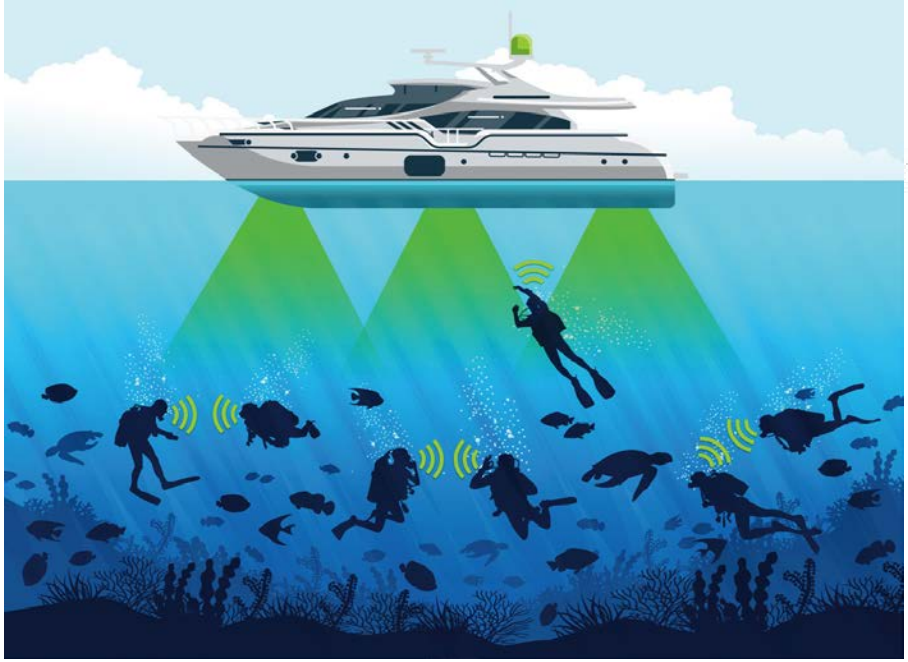
1 Material/chip

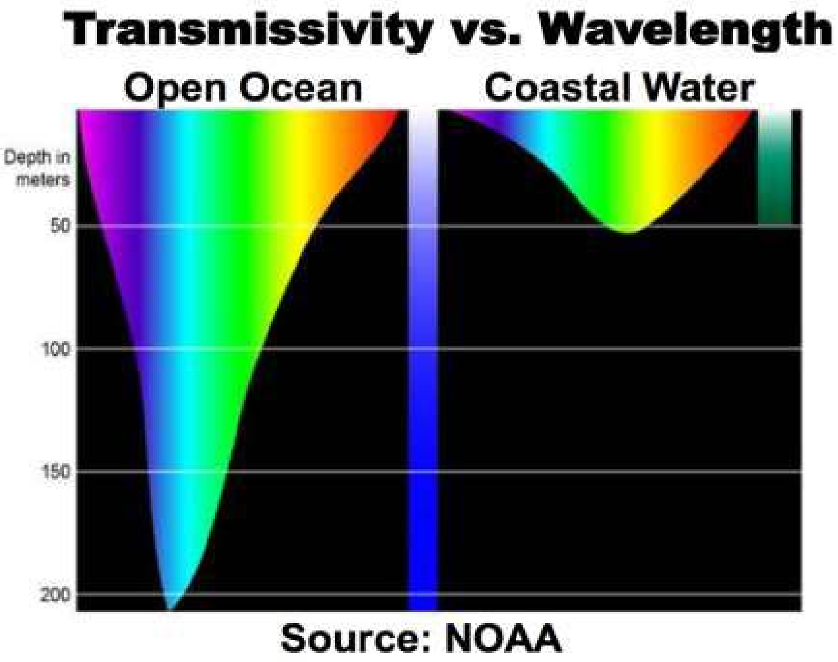
2 High speed system

3 Multiplexing/networking

4 Underwater VLC

Research Motivation of LED based underwater VLC system

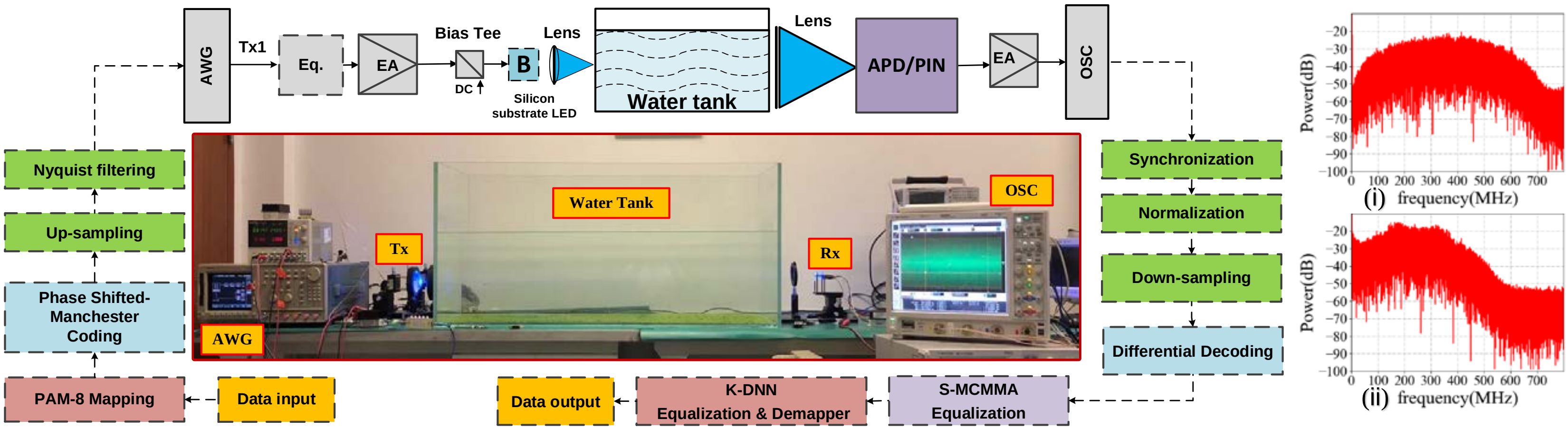




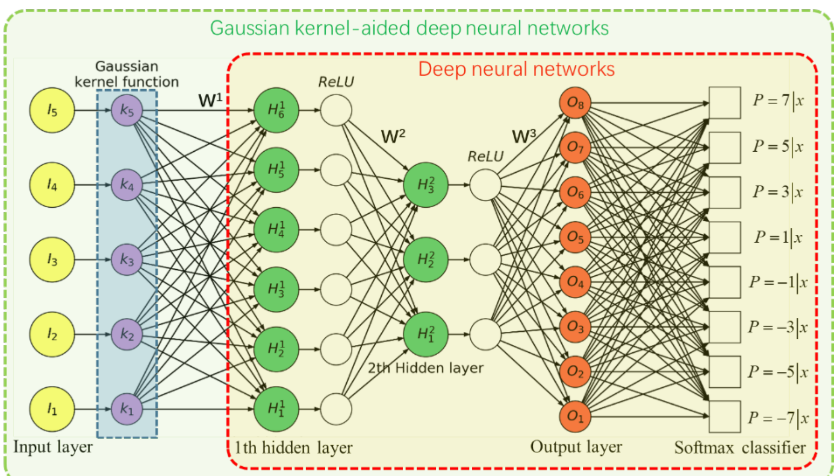
Methods utilizing underwater

- Acoustic communication： long distance and low bitrate (Kbps level)
- RF communication : very short distance and common bitrate (Mbps level)
- LD based VLC : long distance and high bitrate (Gbps level) require precise collimation.
- LED based VLC : long distance and high bitrate (Gbps level)

Underwater PAM8 visible light communication



The structure of the GK-DNN



- Transmission function

$$H^N = f(W_{H^{N-1},H^N} \dots f(W_{H^1,H^2} f(K(W_{K,H^1} \overrightarrow{X}_i))))$$

- Softmax function

$$P(y = L | \overrightarrow{X}_i) = e^{W_{H^N,P} H^N} / sum(e^{W_{H^N,P} H^N})$$

- Weight updating function

$$W_{trained} = \arg_W \min\left(-\sum_{i=1}^{m} q(\overrightarrow{X}_i) \log p(\overrightarrow{X}_i | W)\right)$$

N. Chi, et al, Optics Express, 2018

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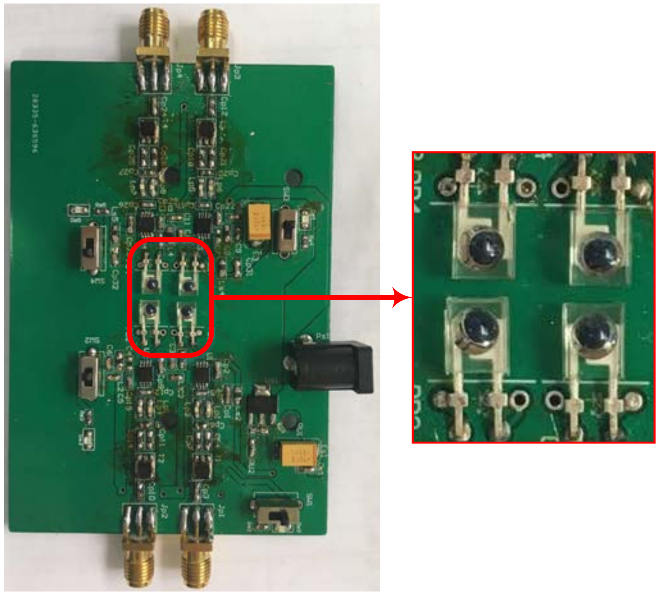
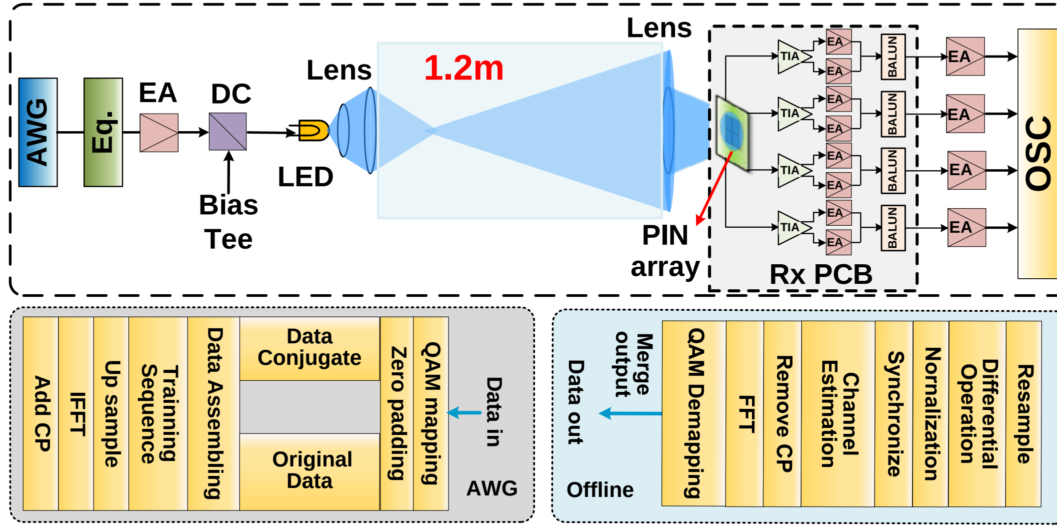
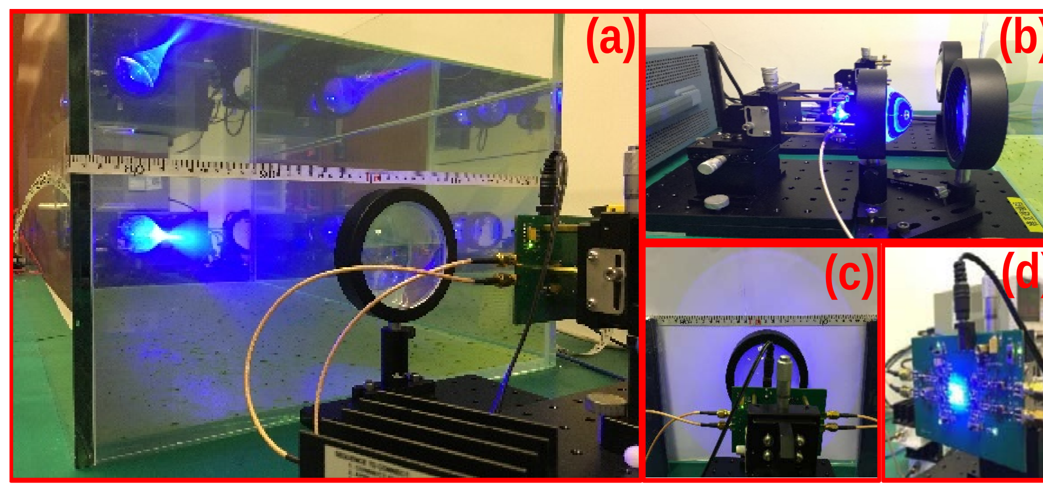
Large-Coverage UVLC System Based On Integrated PIN array Reception





- PIN Photosensitive area: φ=3mm
- Data rate: 1.8Gb/s
- Bandwidth: 300 MHz
- Modulation format: QAM-DMT
- Tank length：1.2m
- 2×2 PIN array receiver，EGC



J. Li, et al., Applied Optics 2019.

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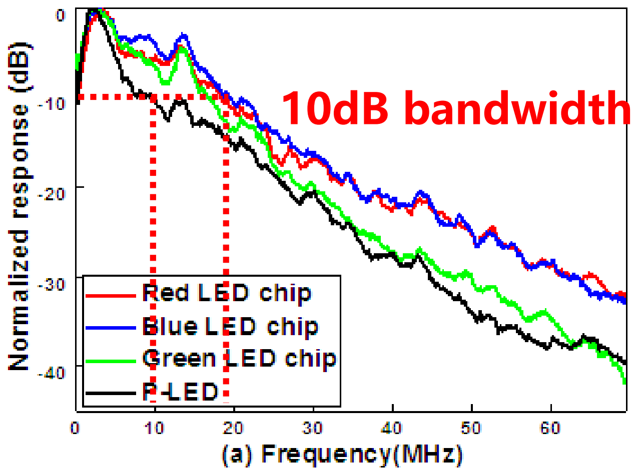
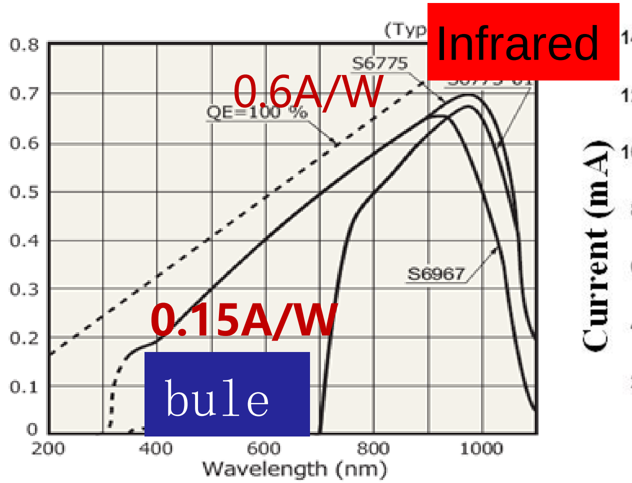
Problems & challenge

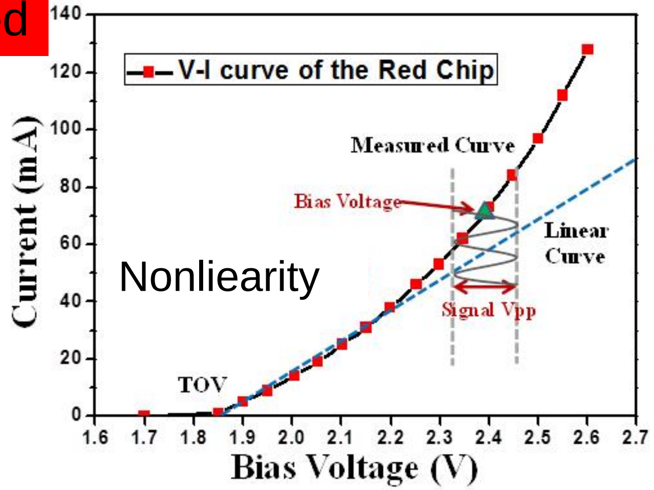
1) the limits bandwidth of LED transmitter

2) low sensitivity in detectors

3) Nonlinearity







- High-speed visible light communication needing optoelectronic chips to achieve the principle breakthrough!

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VLC requires more opto-electronic devices

LED

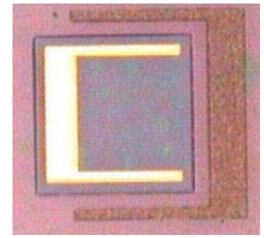
S.Nakamura APL,1995

LD

S.Nakamura JJAP,1995

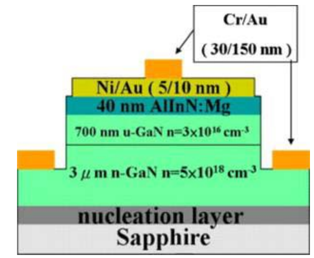
SLD

C.Shen, Opt.Lett,2016



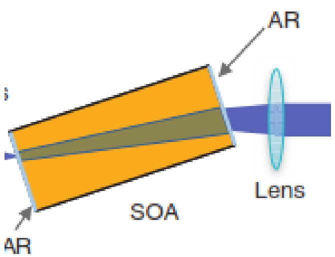
Modulator

E.Sari,APL,2007



PD

S.Chang, J.Electrochem.Soc.2010



Amplifier

R.Koda, APEX,2012

Optical clocking

H.V.Demir, SPIE,2007

Optical switching

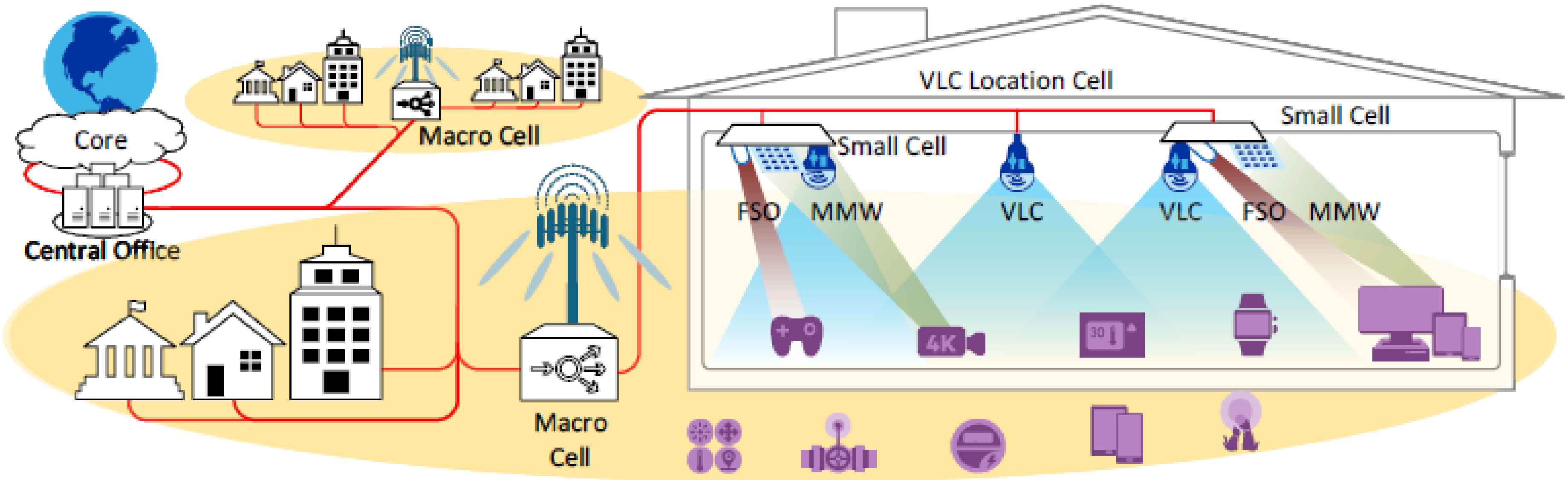
M.Martens, APL,2011

High power LD

R.Koda, APL,2015

- Modulator, multiplex/demux, amplifier, switching……

6G is coming: All-Spectrum Wireless Access Networks



Universal system design aiming to serve all service scenarios through coordination in 6G

- Coordination between multiple bands.
- Centralized architecture, diversified resource usage.

All-spectrum system needs machine learning techniques for performance optimization

- High level bands allocation and system operation
- Low level signal equalization, signal analysis and system parameter estimation

Courtesy by Prof. G.K Chang

Conclusion

High speed

8G/s CAP modulation based on RGB LED
10.7Gb/s OFDM modulation based on RGBYC LED

New devices

Laser, SLD, surface plasmon LED,

New DSP

Modulation, pre/post equalization, machine learning

Future

5G wireless communication, Internet-of-things, vehicle-to-vehicle communications, positioning systems, navigation.

Thanks for your attention!

Visible Light Communications - Smart Environments

Professor Zabih. (Fary) Ghassemlooy

Optical Communications Research Group

Faculty of Engineering and Environment

Northumbria University, Newcastle upon Tyne, UK

http://soe.northumbria.ac.uk/ocr/

e-mail: z.ghassemlooy@northumbria.ac.uk

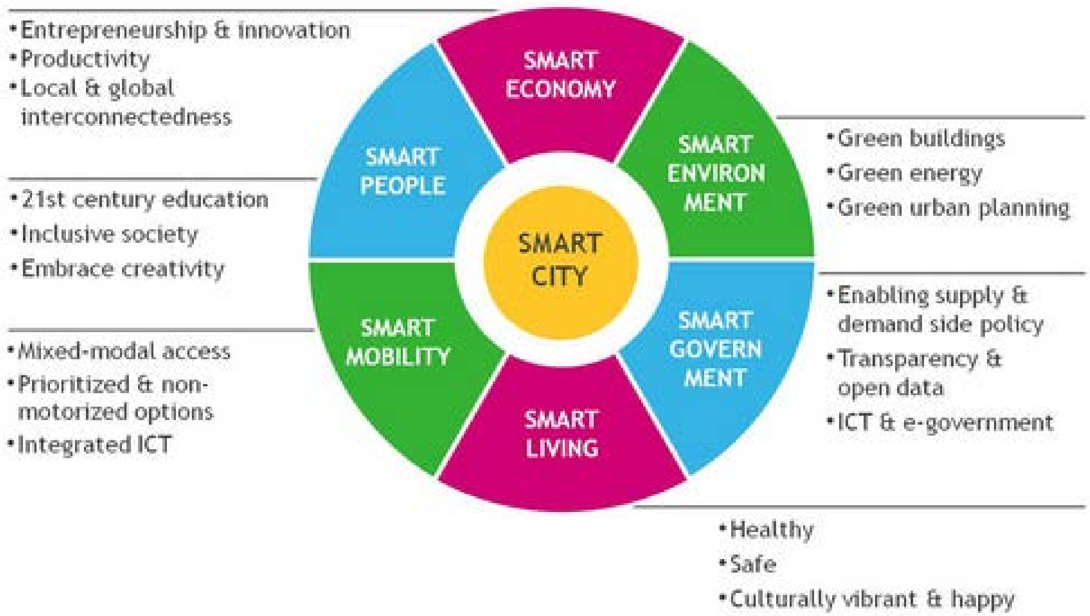
Northumbria University NEWCASTLE

OCRG

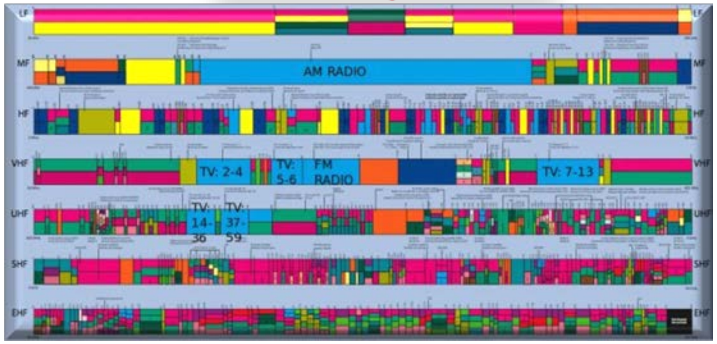
Why the need for

Visible Light Communications Technology?

Global Data Traffic - So What Is the Real Problem?



Massive Data Generated



Spectrum (frequency) congestion

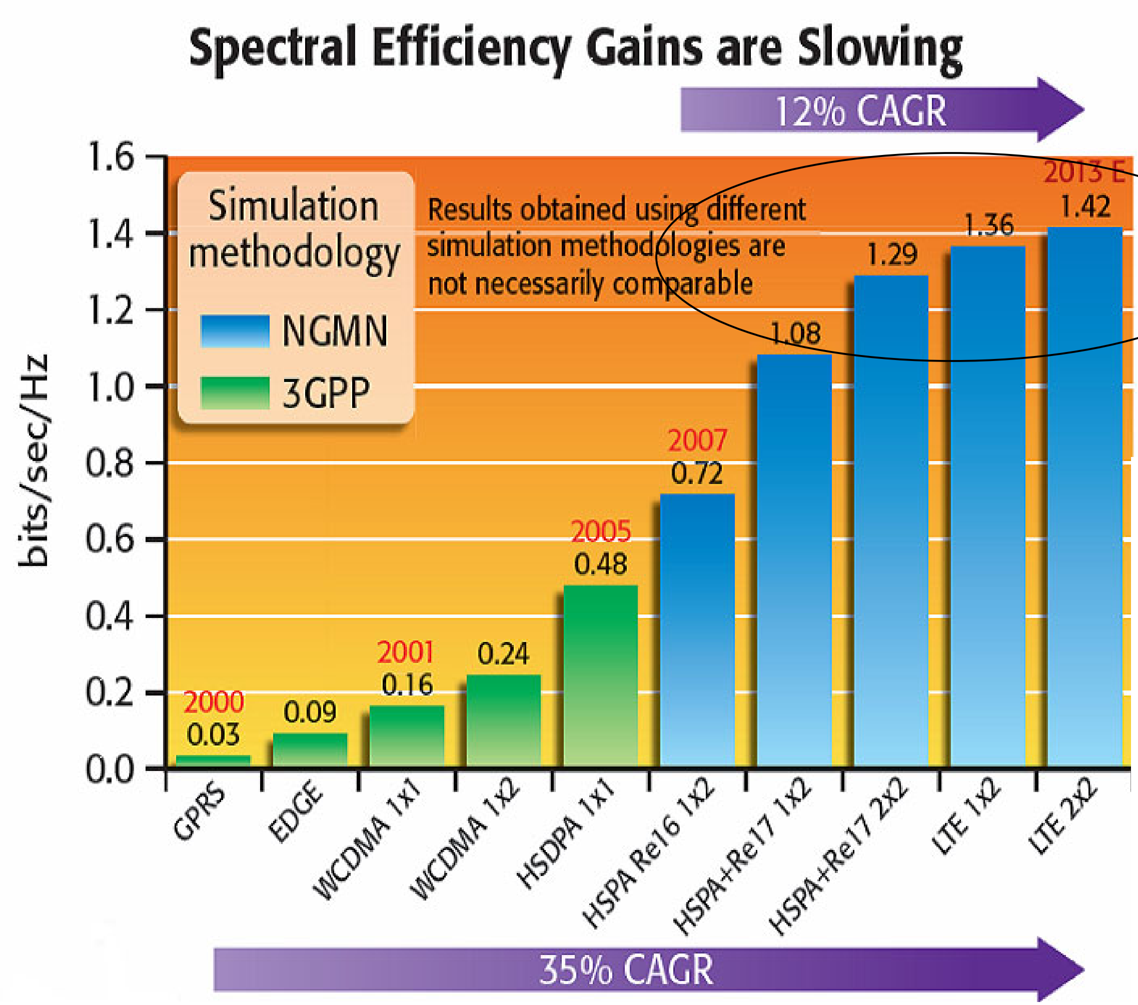
Smart Cities - promote the interaction between the human and the environment, enhance the reliability, resilience, operational efficiency, and energy efficiency.

- **2015** – 1.1 billion connected things
- **2020** – 9.7 billion[1]

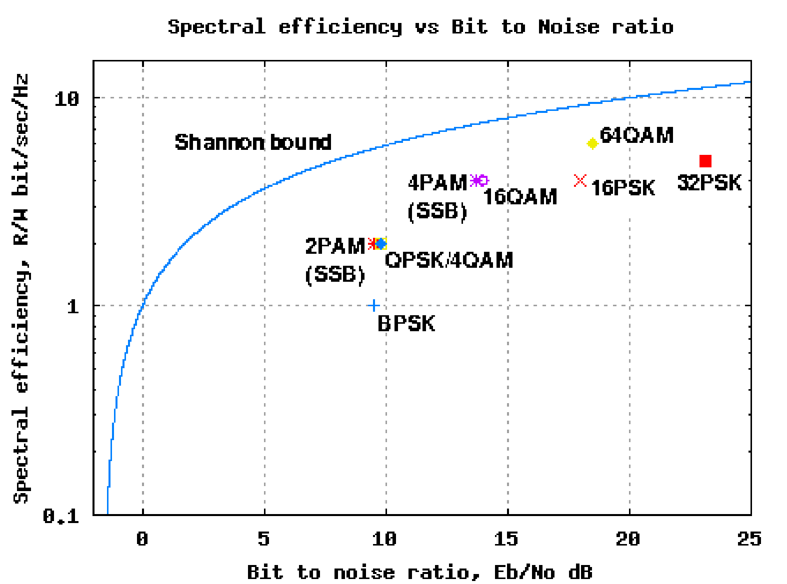
[1] Gartner Inc.

https://techzine.alcatel-lucent.com/smart-cities-are-built-smart-networks

Spectral Efficiency Slowing Down



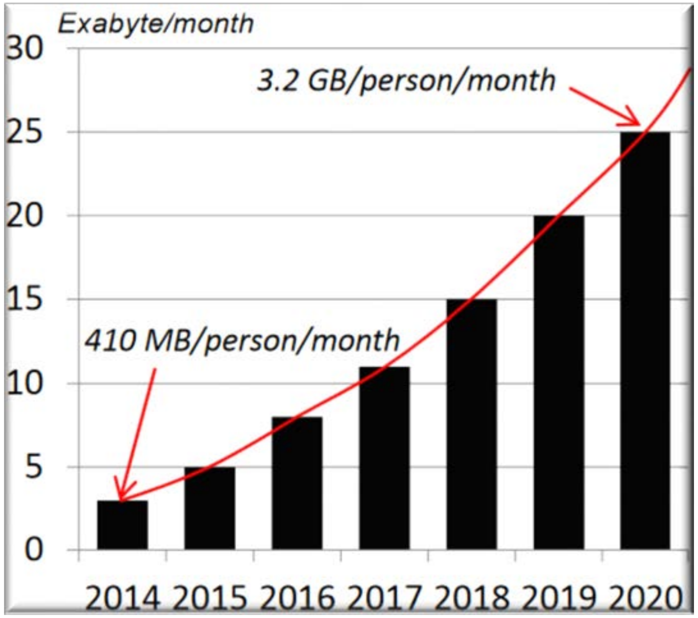
Saturation of The spectrum efficiency gains of cellular systems

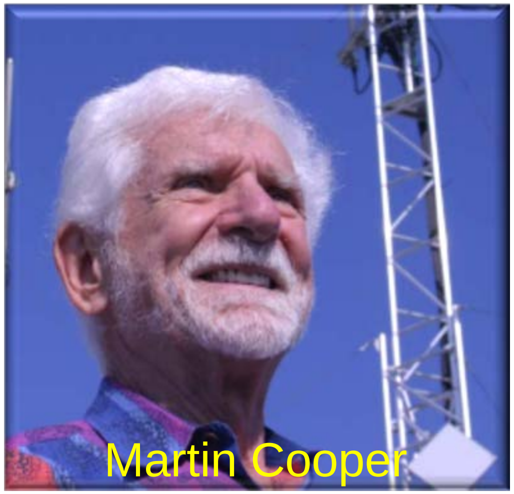


Success of Wireless Communications

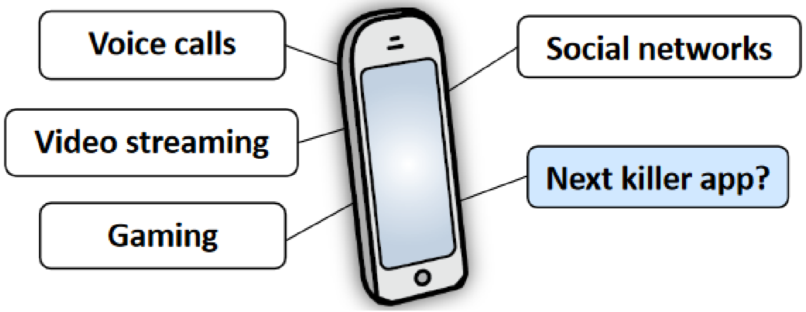
Martin Cooper's law

The number of simultaneous voice/data connections has ***doubled*** *every* ***2.5 years (+32% per year)*** *since the beginning of wireless*





Inventor of handheld cellular phones

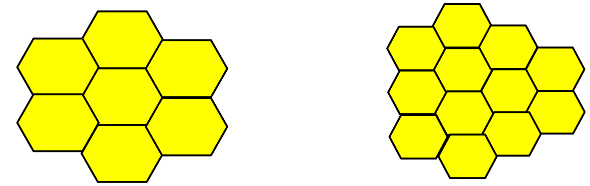


Network Throughput = Cell density × Available spectrum × Spectrum efficiency
(bit/s in area) (Cell/area) (Hz) (bits/s/Hz/Cell)

How to Overcome the Spectrum Congestion? [1/2]

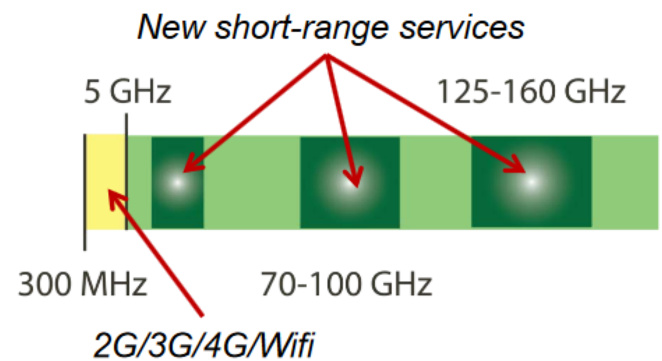
Increased Cell Density

- Divide cell radius by x → x^2 more cells
- Expensive: Rent and deployment cost



Higher Frequencies

- Above 5 GHz: High propagation losses
  - Mainly short range WiFi?

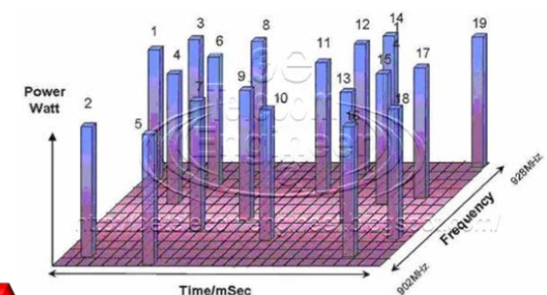


Higher Spectral Efficiency

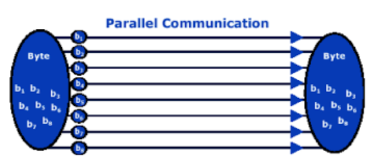
- No big improvements in the past
- **Can it be the driving force in future networks?**

Sharing Resources

- Spectrum hopping
- Spectrum borrowing



Advance Modulation Coding



More Efficient Protocols

Northumbria University NEWCASTLE

OCRG

How to Overcome the Spectrum Congestion? [2/2]

By 2020 in many markets

5G

Vision

Target:

- Very high dense deployment
- Very high capacity: 10-100 Gb/s
- Very low latency; Distributed access; Scalability

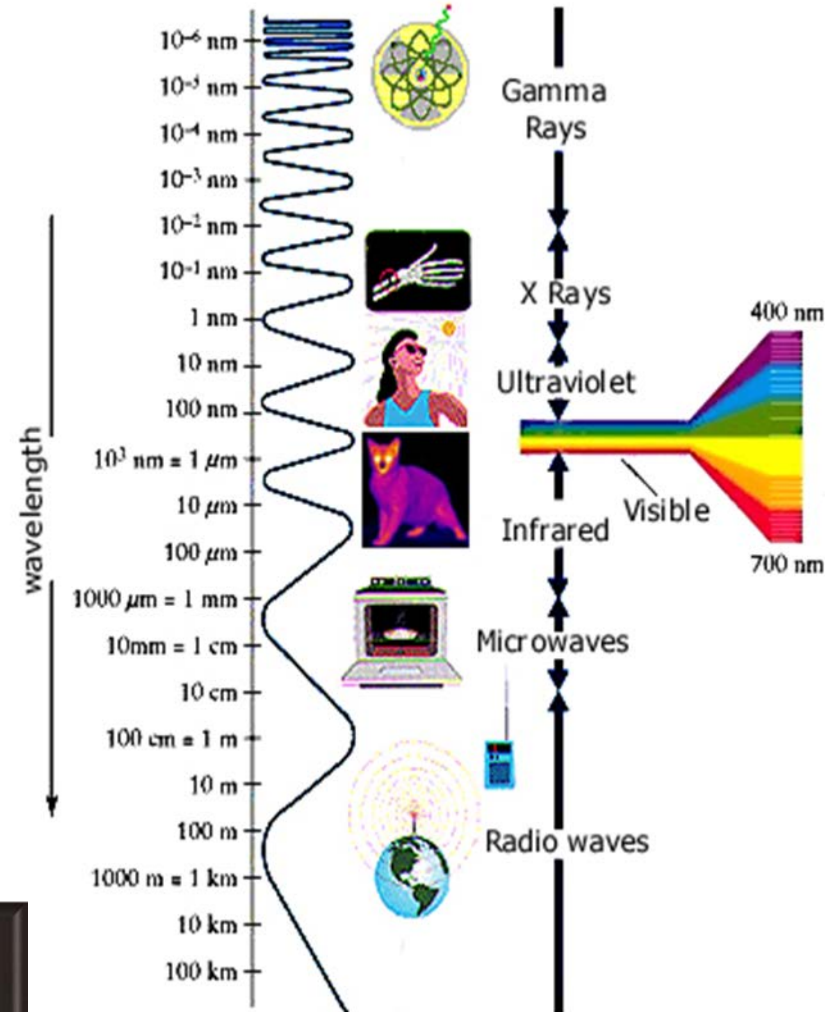
Will not be based on a single access technology, but a number of different complementary technologies:

- **Massive MIMO**
- **Super-dense meshed cells/macro-assisted small cells**
- **Enhanced VoIP;**
- **New modulation/coding**
- **MMWave – 15 GHz; 28 GHz; 60 GHz; > 70 GHz, etc.**
- **VLC?**

- L. Hanzo, et al, "Wireless myths, realities, and futures: From 3g/4g to optical and quantum wireless," Proceedings of the IEEE , vol. 100, pp. 1853–1888, May 2012.
- Wu S, Wang H, Youn C H. Visible light communications for 5G wireless networking systems: from fixed to mobile communications. IEEE Network, 2014, 28(6): 41

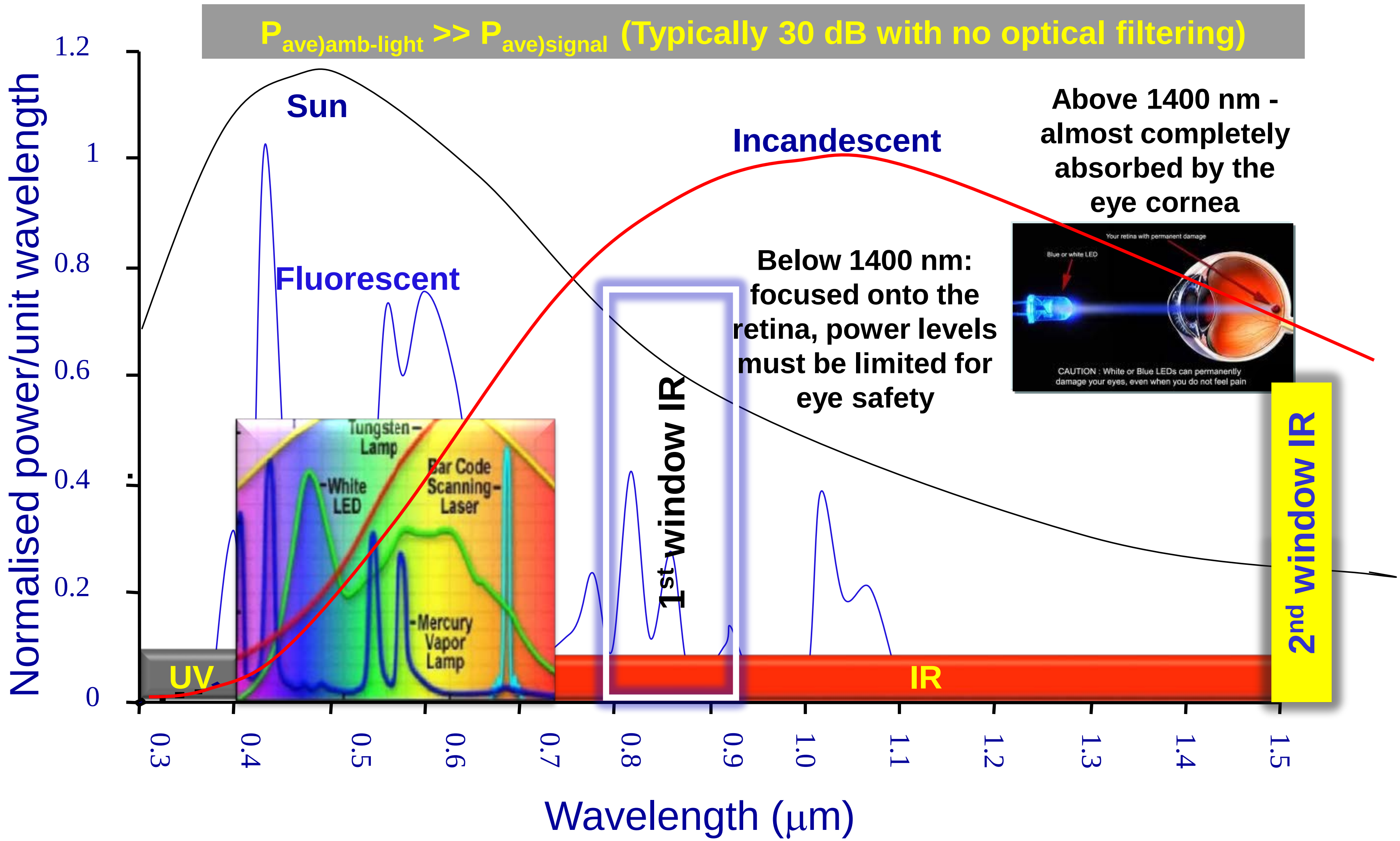
Visible Light Communications (VLC)

- Concept
- Typical Applications
- Some data on VLC
- Concluding Remarks

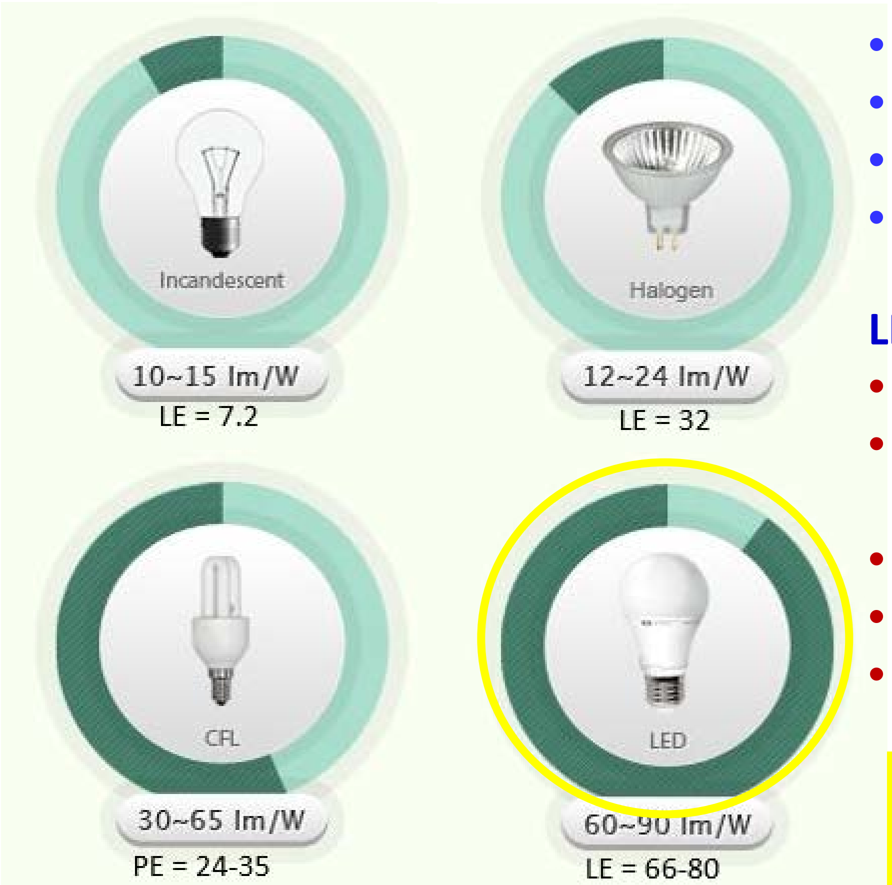


Prof Z Ghassemlooy

OWC - Transmission Windows & Power Spectra of Ambient Light Sources



VLC - General Lighting Sources



- **LEDs** - 30,000 to 100,000 hours - 6 to 30 years
- **Incandescent bulbs** - 1000 to 5000 hours
- **CFLs** - 8,000 to 10,000 hours
- **Fluorescent tubes** - 20,000 to 50,000 hours

LED widespread Benefits by 2025[1]

- Lower electricity demands for lighting by 62%.
- Reduce carbon emissions by 258 million metric tons.
- Diminish amount of materials in landfills.
- Prevent construction of 133 new power plants.
- Save $280 billion.

Market is expected to grow 30.8% compound annual growth rate (CAGR) from 2012's 12.92 billion US dollars in 2019 to grow to $ 86.08 billion.

PE: Power efficiency
LE: Luminous efficiency

[1]The U.S. Department of Energy

LEDs offer much faster SWITCHING speed!

What Can We Do With Switching of LEDs?

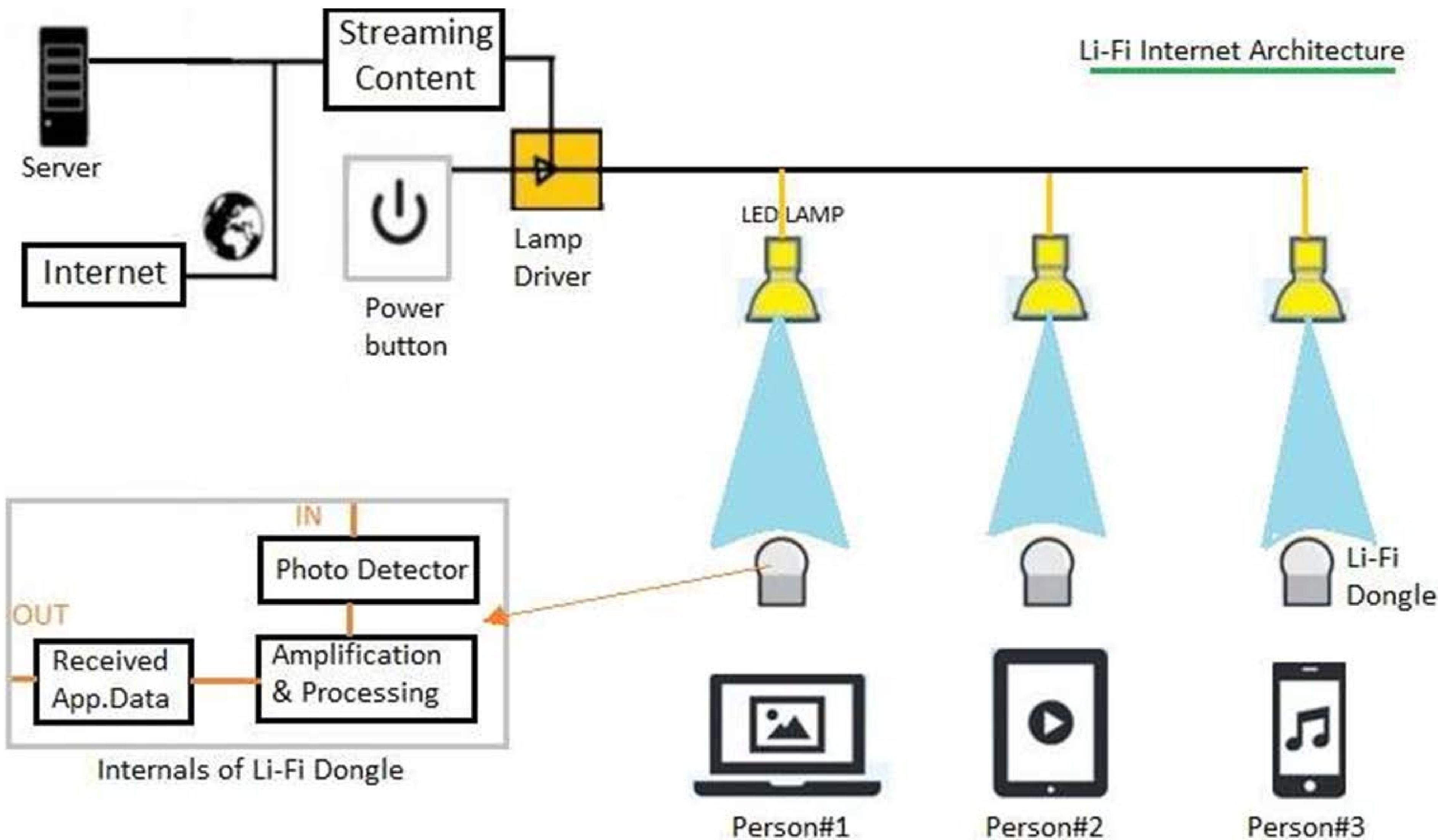
Illumination

Data Communications

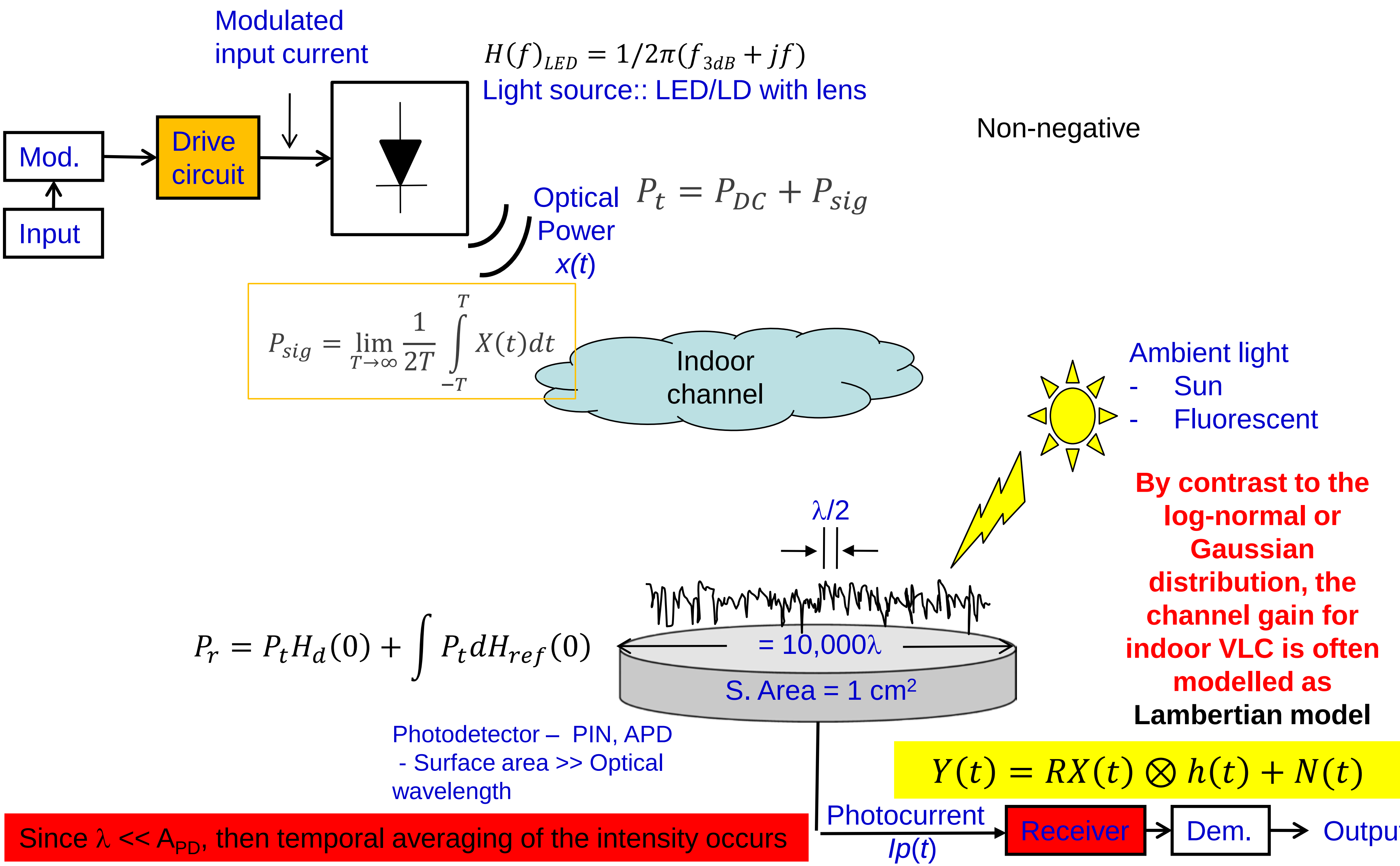
Sensing

Indoor Localization

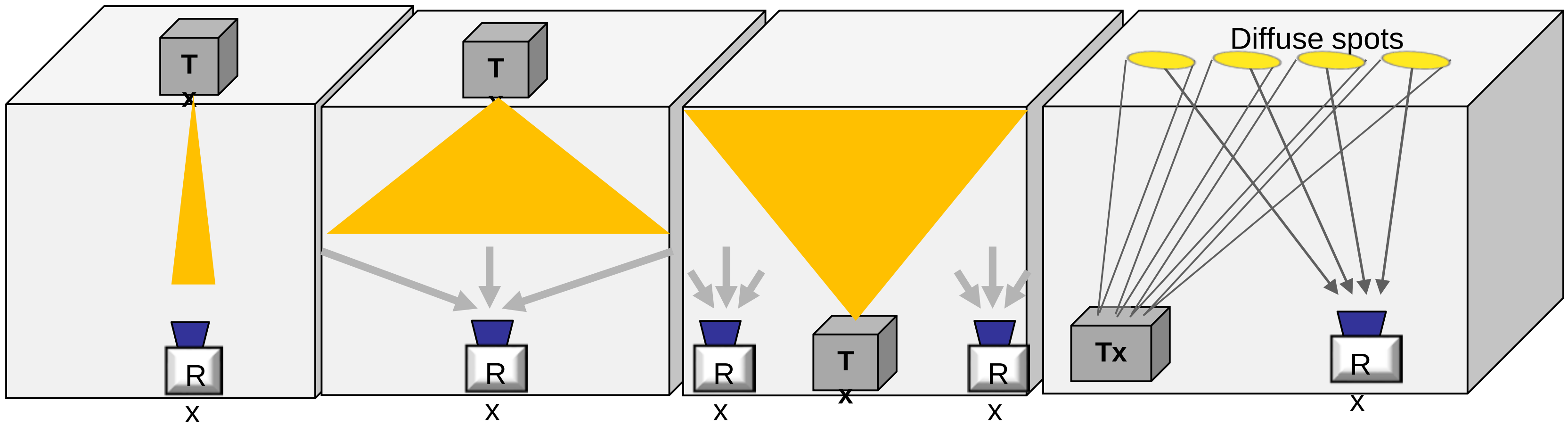
VLC – The Concept

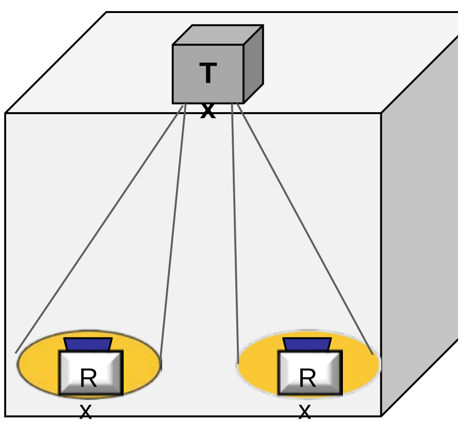


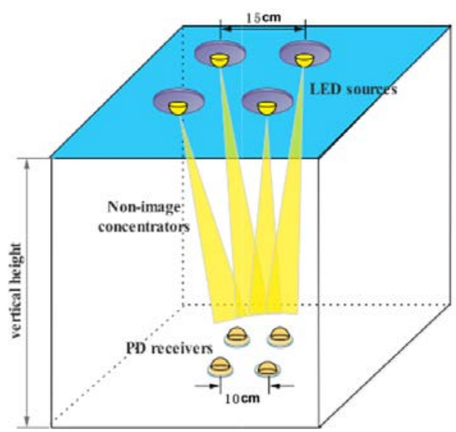
VLC – System Concept

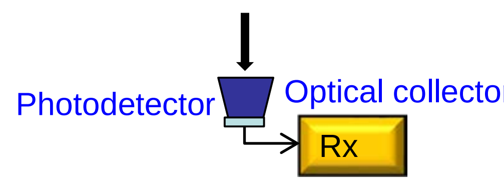


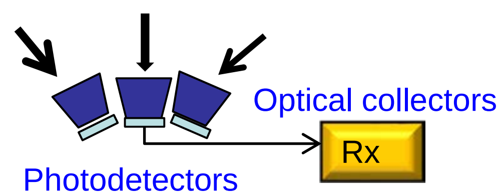
OWC – Link Configuration

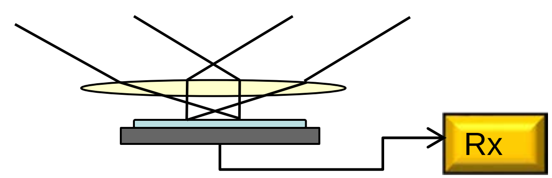






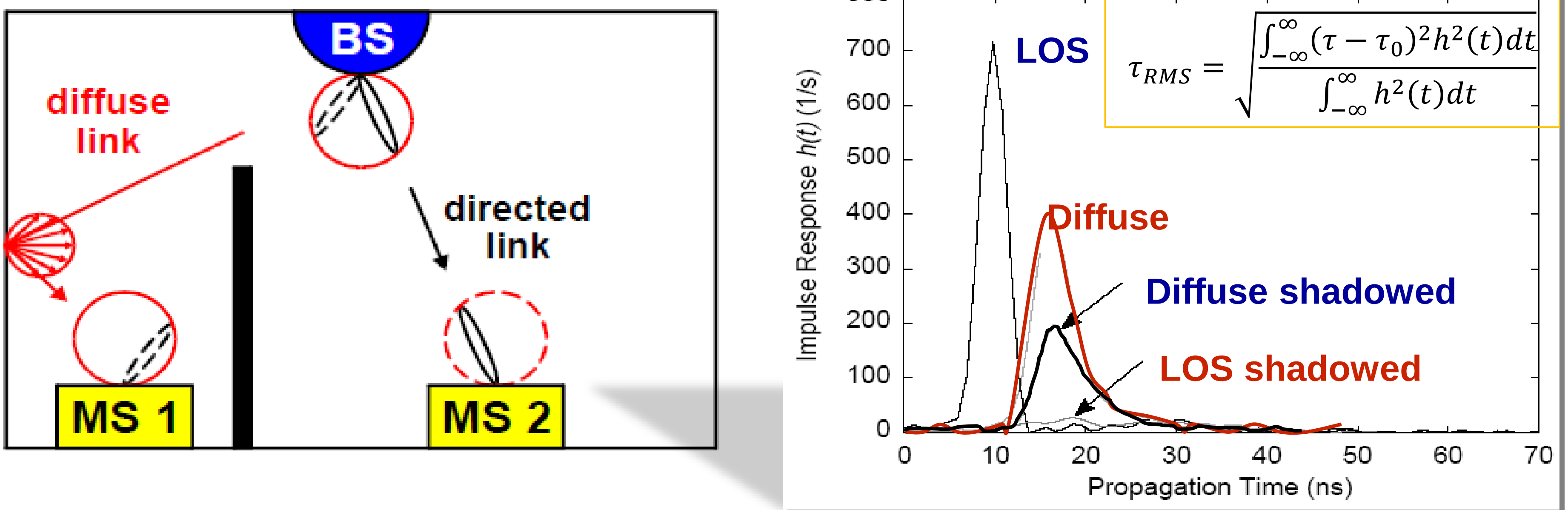






VLC – Transmission Modes – LOS + NLOS

BS: base station, MS: mobile station

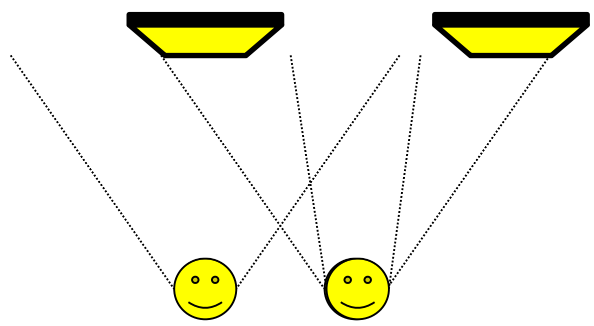


- LoS – Best data, but mobility and blocking is a problem
- Non-line-of-sight (NLOS)
  - Diffuse reflections → less power
  - Wide field-of-view → blocking is less relevant → inherent mobility support
  - Multipath → low bandwidth

VLC – Noise and Interference in DD

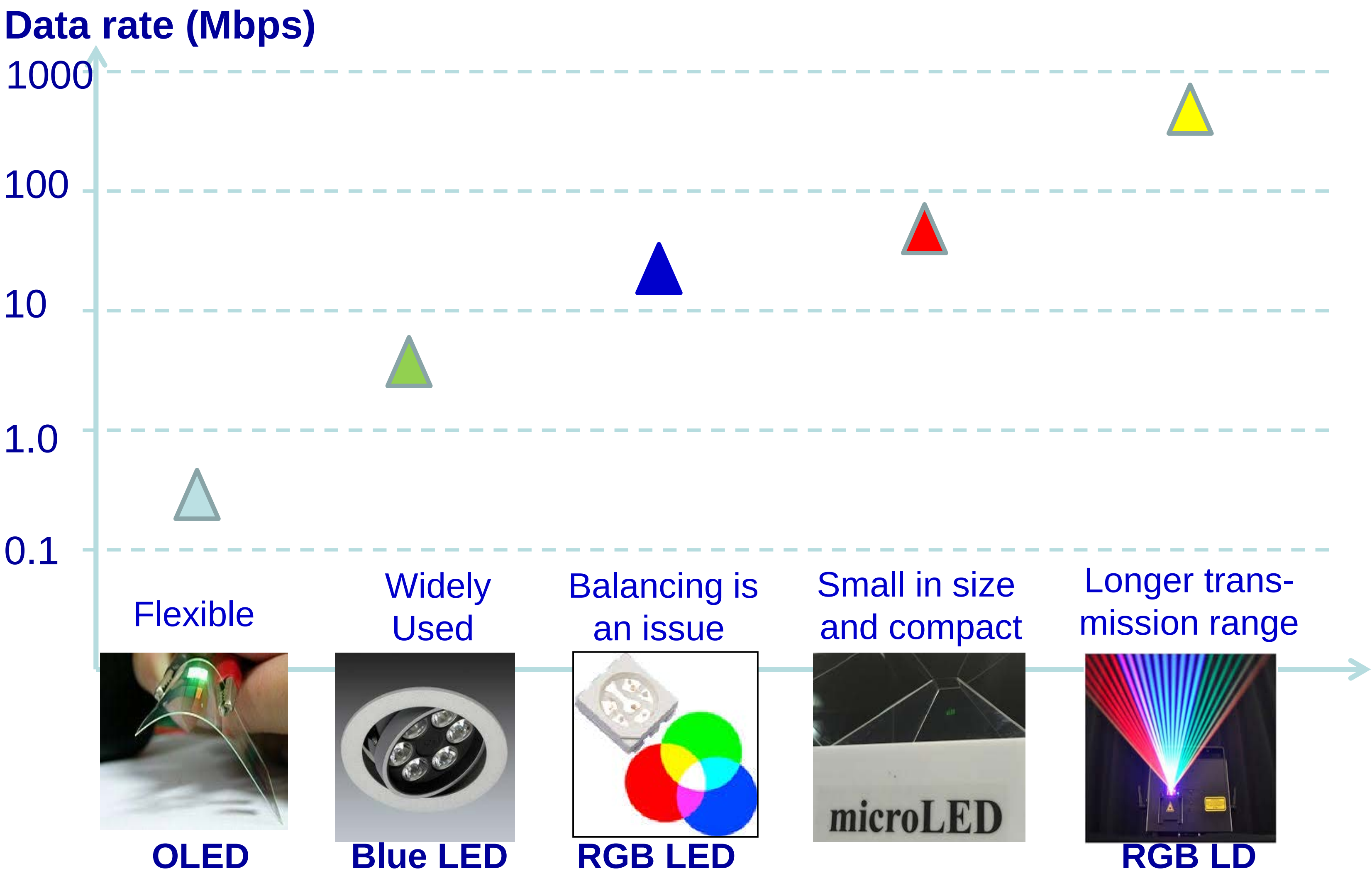
- Defined by $$\mathrm{SINR} \triangleq \frac{\left(RHP_{sig}\right)^2}{{I_{int}}^2 + {\sigma_n}^2} = \frac{\left(RHP_{sig,x}\right)^2}{\left(R\sum_{i\neq x} H_i P_{sig,i}\right)^2 + {\sigma_n}^2}$$

- Received SINR can be categorized by three scenarios:
  - **LOS, Multipath:** P_{sig} is much larger than interference power.
  - **LOS, LOS**: Multiple luminaires are in the device FOV.
  - **Multipath, Multipath:** LOS path does not exist.



T. Little, Boston University, USA

VLC – Light Sources

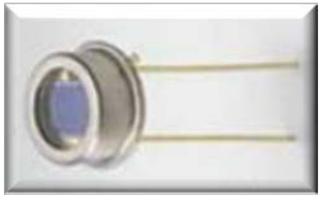


1- Grubor, Jelena, et.al, 33rd European Conf. and Exhibition of , vol., no., pp.1-2, 16-20 Sept. 2007.

2- D. Tsonev, H. et al, A 3-Gb/s single-LED OFDM based wireless VLC link using a gallium nitride LED, IEEE Photonics Technology Letters, vol. 36, pp. 637640, Apr. 2014.

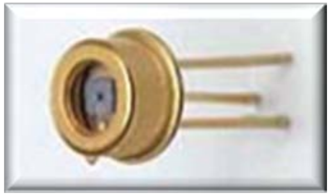
3- P. A. Haigh, Z. Ghassemlooy, et al , Visible light communications using organic light emitting diodes, IEEE Communications Mag., 51, 8, pp. 148154, 2013

VLC – Detectors



PIN photodiode

- low cost, large area
- limited sensitivity



Avalanche photodiode (APD)

- higher sensitivity
- smaller area
- high reverse bias → higher cost

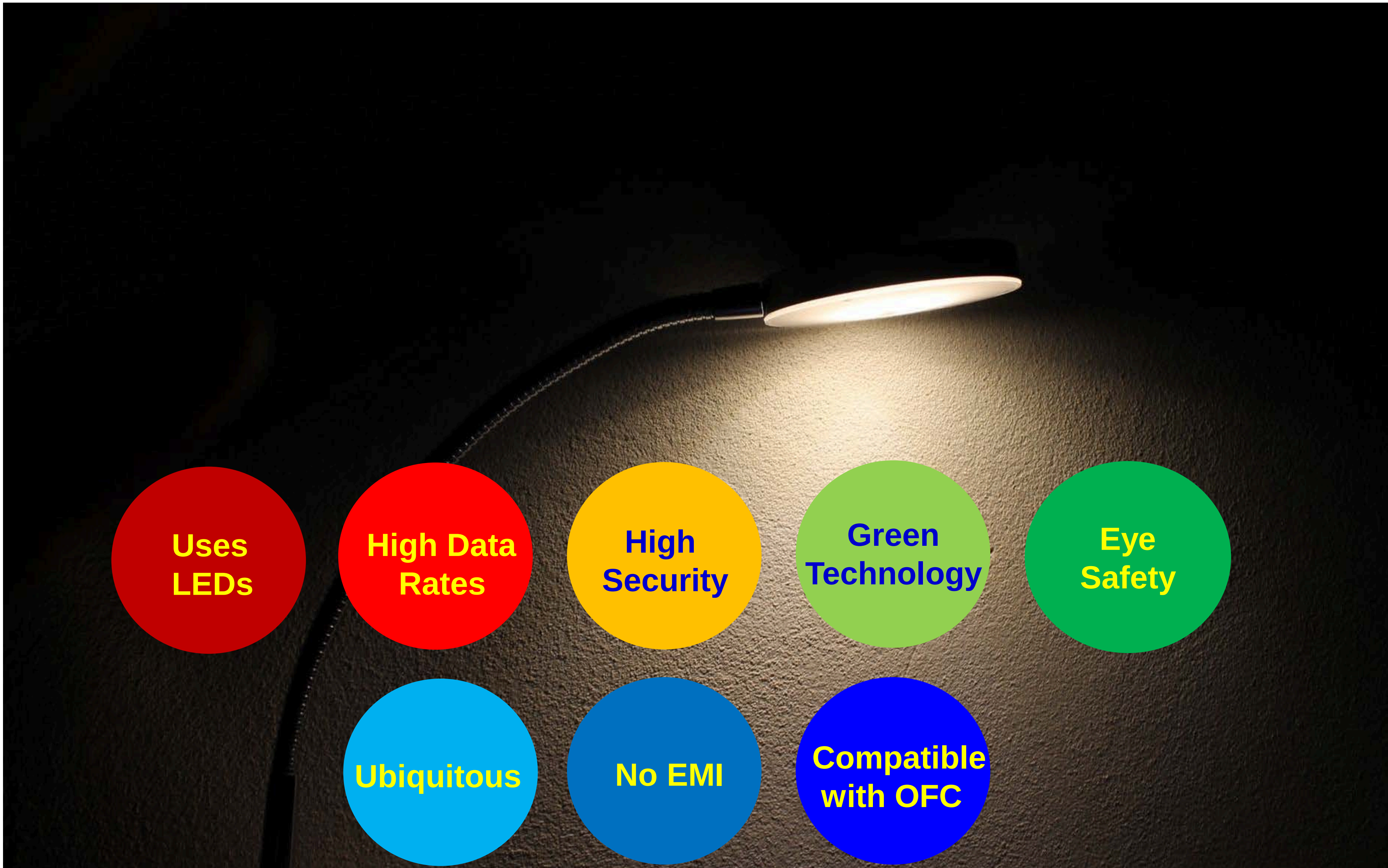
Issue with a single-element PD
- cannot be used effectively in direct sunlight.

Image sensors:

- **CCD type**: low cost, slow due to serial read-out
- **array type**: pixels are operated like parallel photodiodes → fast but high price, mass market would be revolutionary for optical wireless
- ability to **separate sources spatially**

J. Rufo et al.: Experimental Evaluation of Video Transmission Through LED Illumination Devices, 2013

VLC – Features



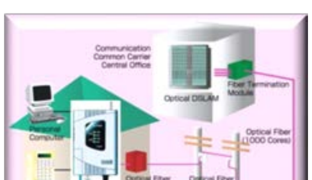
Northumbria University NEWCASTLE

OCRG

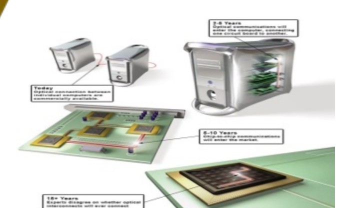
VLC – Applications

Where LED is used for illumination can be used for:

- Mining
- Smart lighting
- Museum
- Hospital
- Indoor GPS
- Finance
- IoT
- Highway
- Parking
- Others
- Military
- Library
- School
- Train/Bus station
- Smart homes
- Airplane
- Smart Manufacturing



Home access

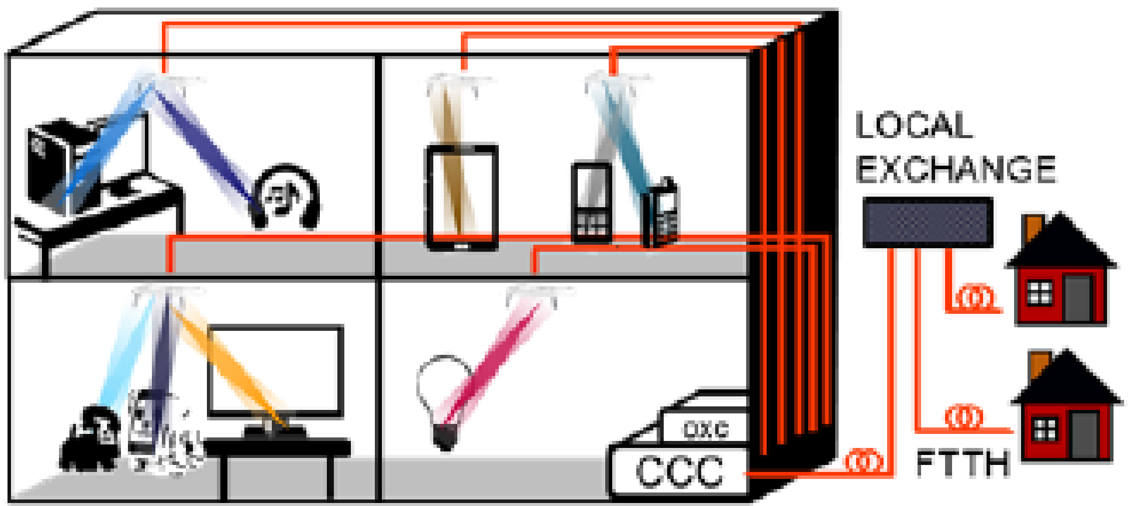


Board
Inter-Chip
Intra-Chip

VLC – Access Network

Oh Chin Wan, et al, Low-crosstalk Full-duplex All-optical Indoor Wireless Transmission with Carrier Recovery, IEEE PTL, 2016, Eindhoven University of Technology

- **Connected to indoor network via central communication controller (CCC)**
- **Data routed to different rooms via optical cross-connect and a fiber-backbone network.**



- Still no decision been made
- **WiFi** - typically offers a lower channel capacity, but highly mobile
- **IR – Mature technology**
- **VLC** – LED and Laser
  - Broad beam profile of LEDs - a trade-off between the link budget and bandwidth
  - Laser source - The need for beam steering, which leads to latency and complex receiver hardware.
- **Hybrid**

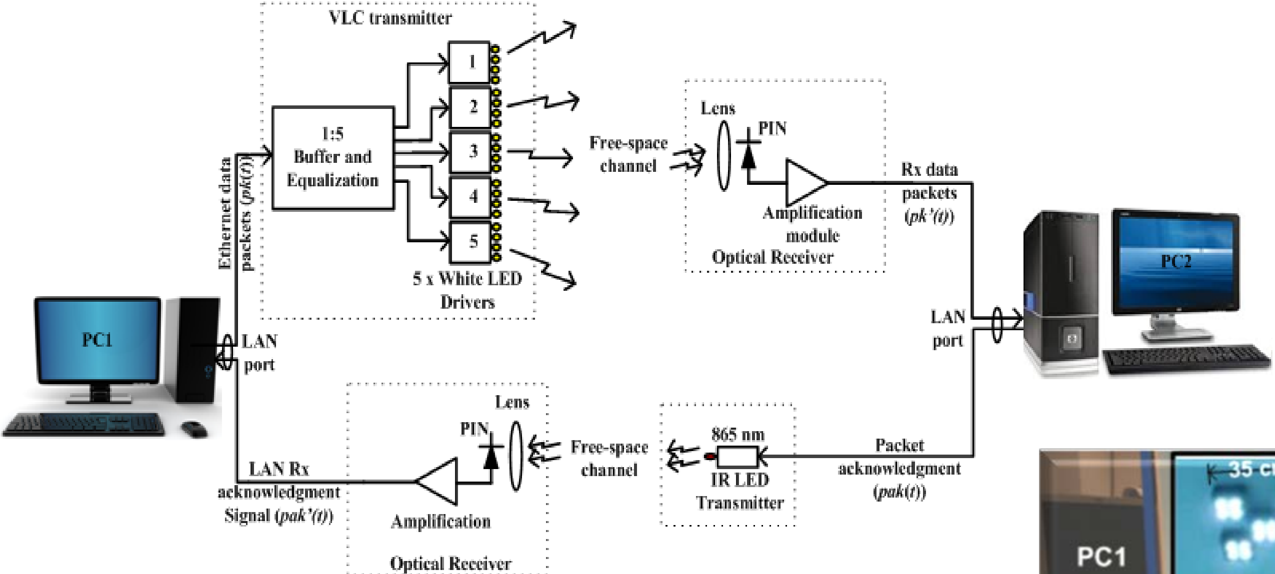
K. Wang et al., "Experimental Demonstration of Full-Duplex Optical Wireless Personal Area Communication System with 16-CAP Modulation," in *Proc. OFC*, Los Angeles, 2015, paper M2F.7

Project 1

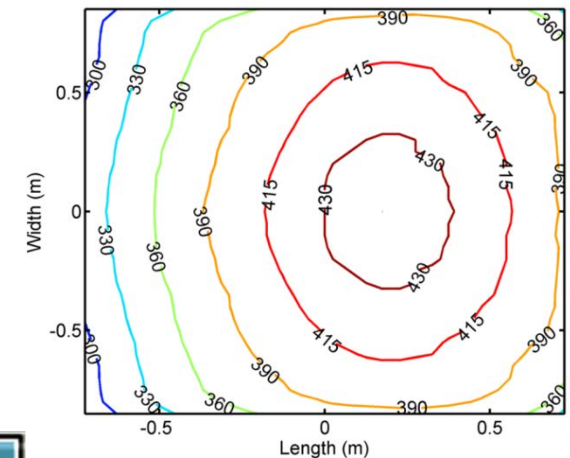
VLC Ethernet

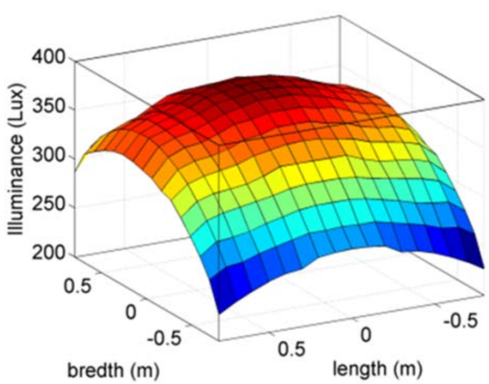
VLCs – Bidirectional Ethernet System (VLC – IR)

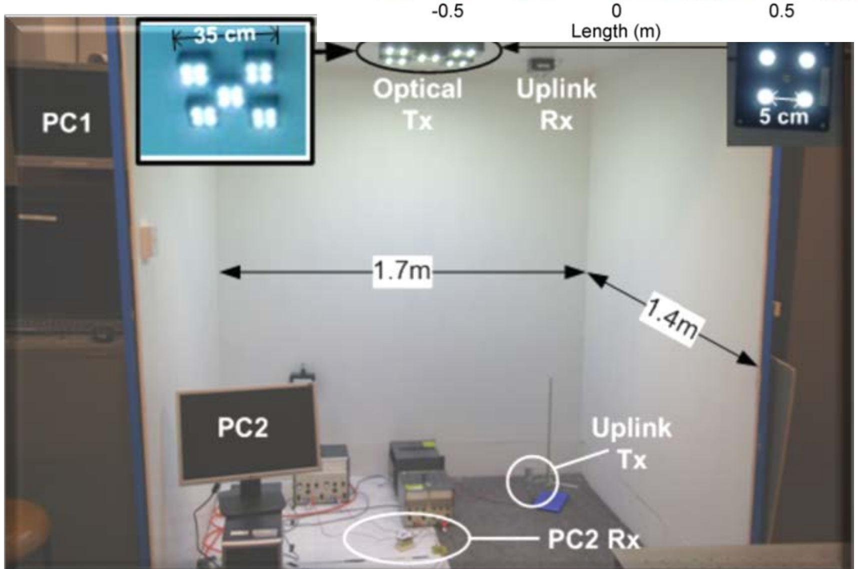
To increase bandwidth



Illumination Pattern







Burton, A., Bentley, E., Le Minh, H., **Ghassemlooy, Z.**, Aslam, N., and Shien-Kuei L.: "Experimental demonstration of a 10BASE-T Ethernet visible light communications system using white phosphor light-emitting diodes," IET Circuit, Devices and Systems, 8 (4), pp. 322-330, 2014.*

Project 2

VLC

Northumbria University NEWCASTLE

UCL

EPSRC Pioneering research and skills

Multifunctional Polymer LEDs with VLC – Oct. 2016- Non. 2019

- All WDM-VLC systems reported use dichroic filters that work by absorbing the radiation outside their passband to eliminate the crosstalk prior to detection [1].
- Limited bandwidth of 35k Hz
- Our OLED have bandwidth 0f 900 kHz.

WDM Demultiplexer Configurations

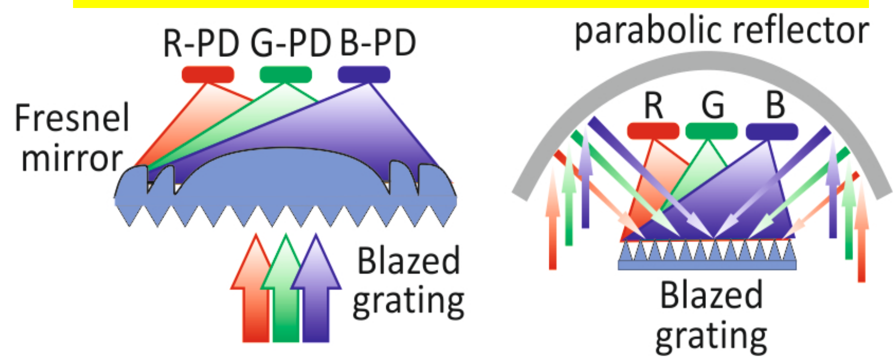
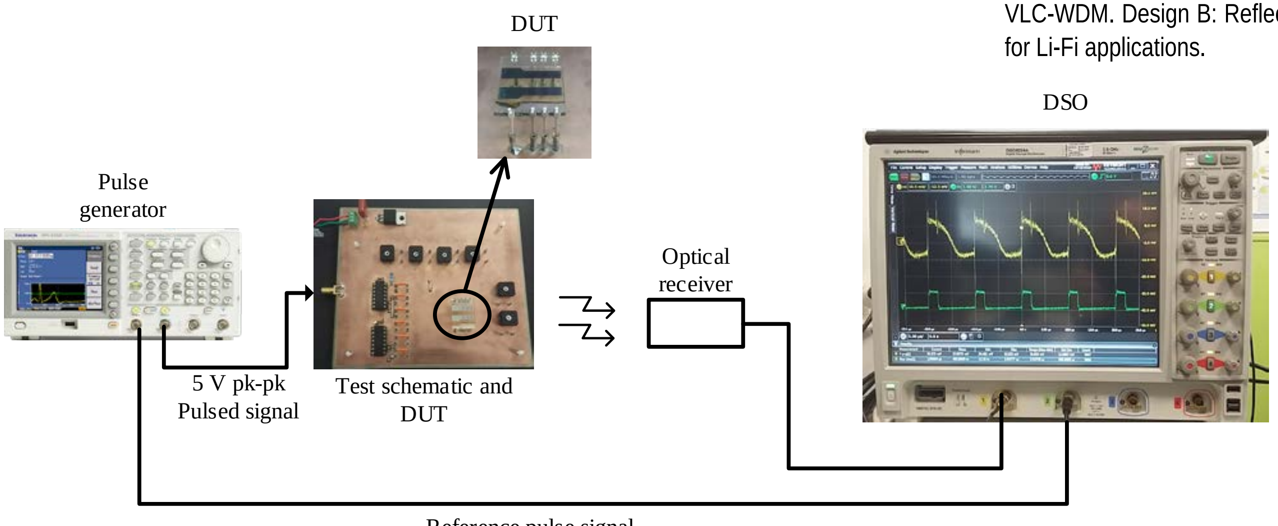
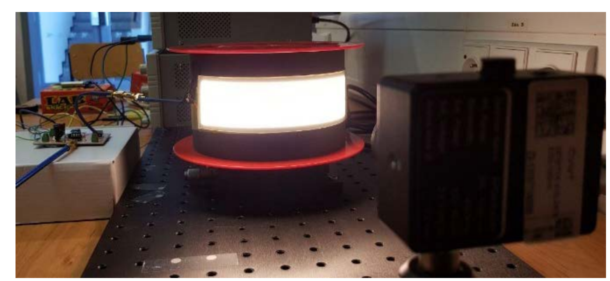


Fig. 2: Design A: Transmissive Mode, a colour separating and focusing optical system for VLC-WDM. Design B: Reflective Mode. A colour separating and focusing optical system for Li-Fi applications.

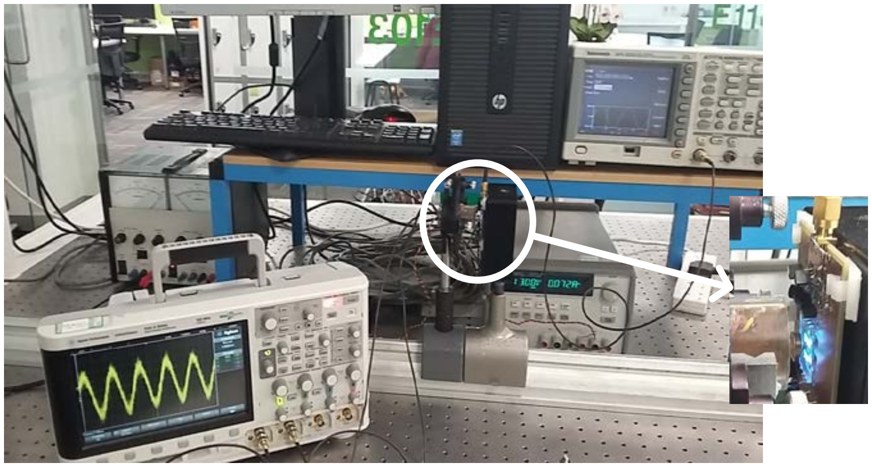


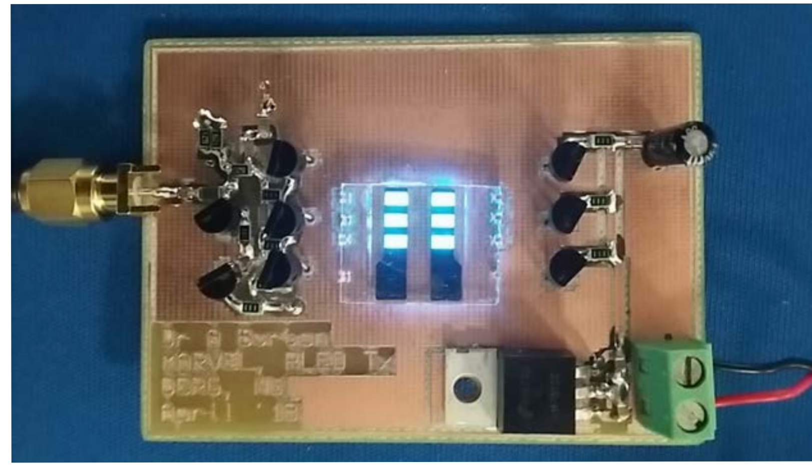


Haigh, P. H., Chvojka, P., Ghassemlooy, Z., Zvanovec, S., and Darwazeh, I.: "Non-Orthogonal Multi-band CAP for Highly Spectrally Efficient VLC Systems," arXiv preprint arXiv:1806.08302., 2018

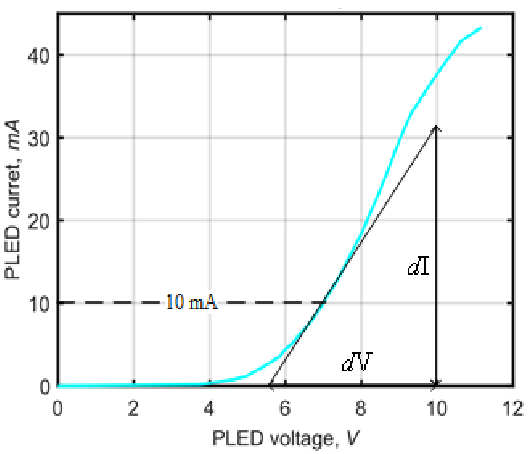
[1] M. R. Perrett and I. Darwazeh, "Characterisation and verification of an FPGA signal generator for spectrally efficient wireless FDM," in *Telecommunications (ICT), 2012 19th International Conference on*, 2012, pp. 1-5.

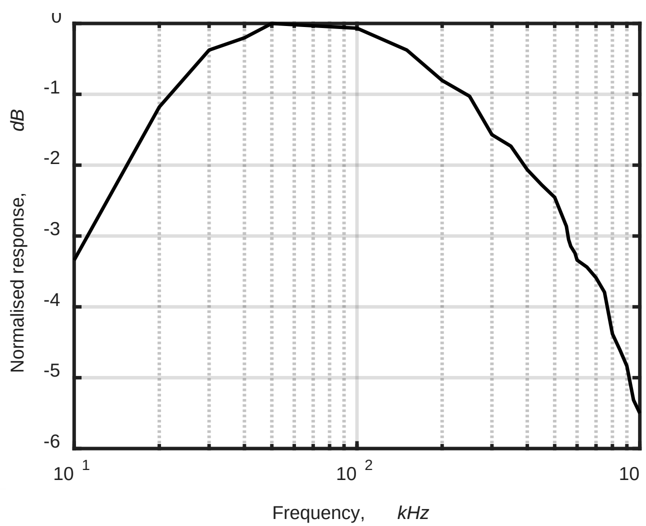
Multifunctional Polymer LEDs with VLC





A bias current of 10 mA





3 dB frequencies are 11.3 and approximately ~**600 kHz**. The upper 3 dB bandwidth is higher the bandwidth of than existing OLED devices (300 kHz)

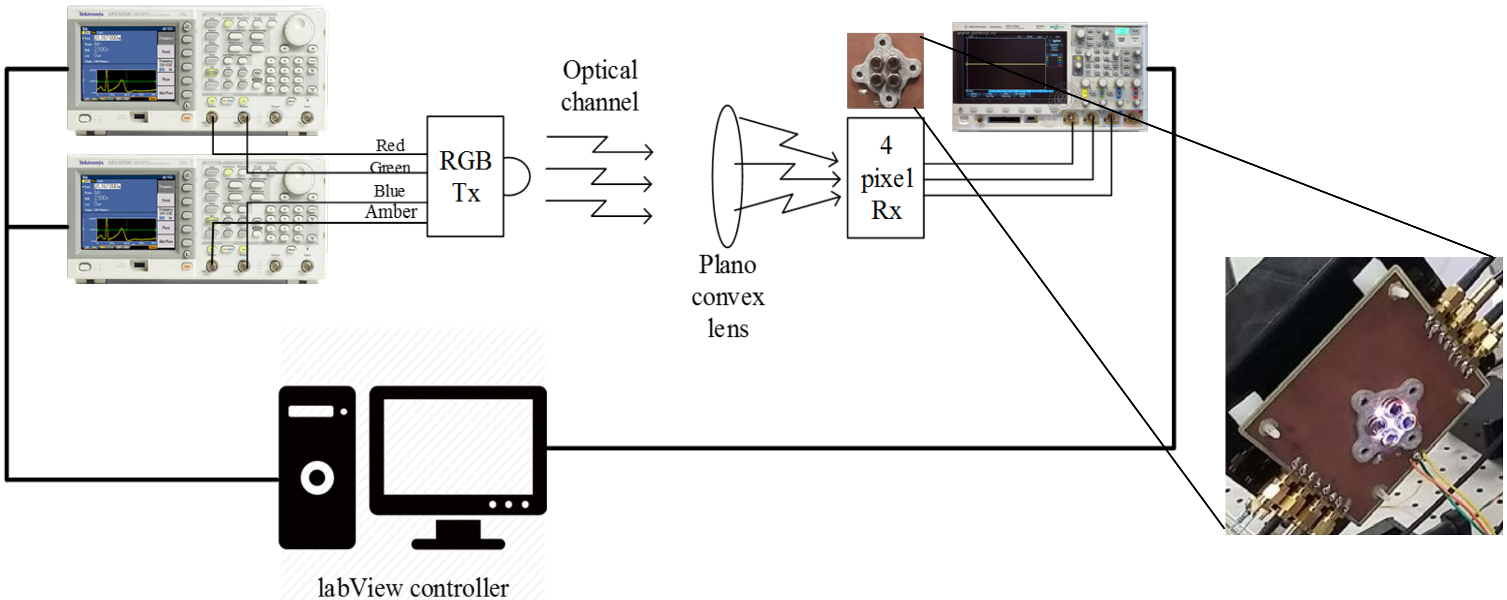
[1] P. A. Haigh et al., "Organic visible light communications: Methods to achieve 10 Mb/s," 2017 IEEE Photonics Conference (IPC), Orlando, FL, 2017, pp. 553-554.

Project 3

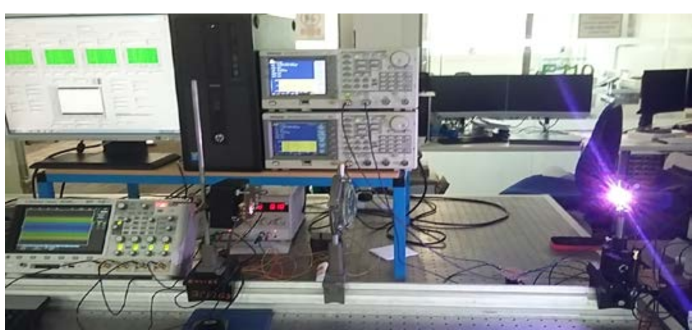
RGB - VLC

Defocused RGB MIMO VLC

De-multiplexing R, G and B streams out of the cumulative white beam to recover the data on each colour without using optical filters.

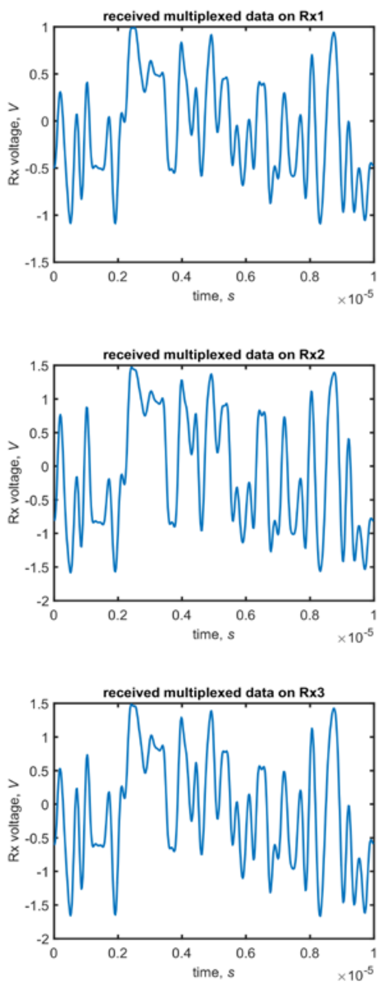


Only 3 PD are used



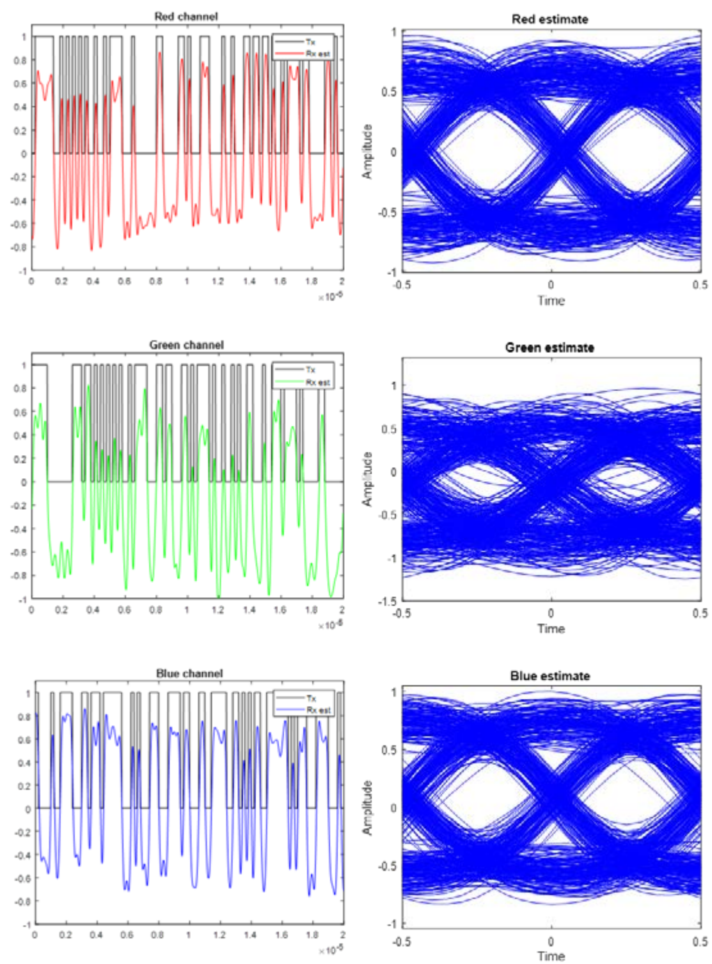
De-focused RGB MIMO VLC

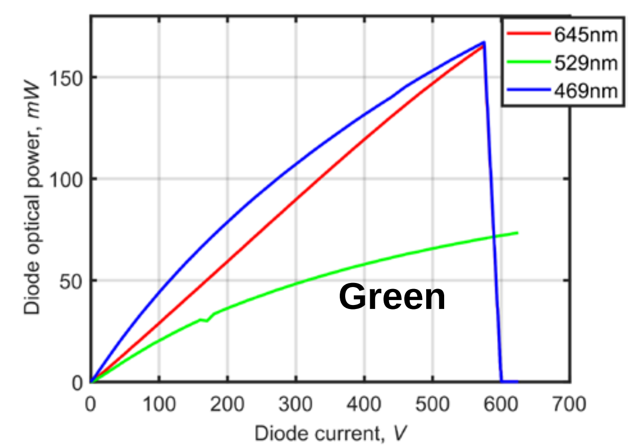
Captured multiplexed data on Rx1, Rx2 and Rx3



Portions of estimates of Tx data via R, G and B emitters

[Txed sequence (black)]





Point - It is possible to recover each of the R, G and B transmitted data and demultiplex signals using DSP, as an alternative to using optical filters by employing the well-known zero-forcing MIMO technique.

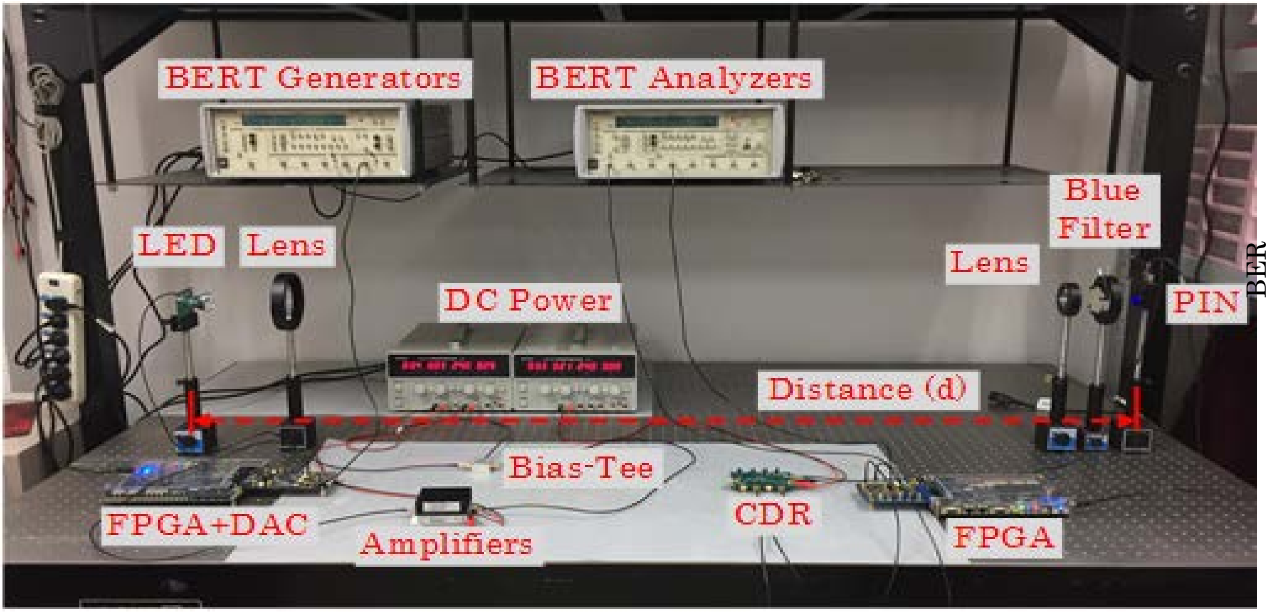
Project 4

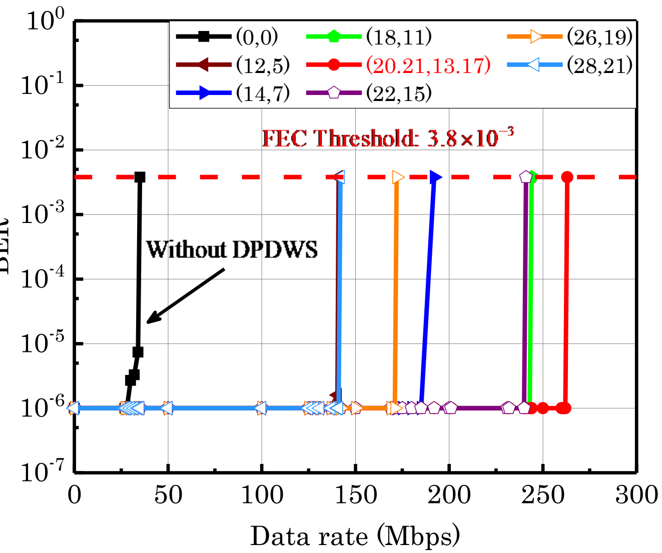
VLC IoT

VLC – Real Time 262 Mbps for IoT

Northumbria Univ. UK, BUPT, China

A Single LED and Digital Pre-distortion Waveform Shaping



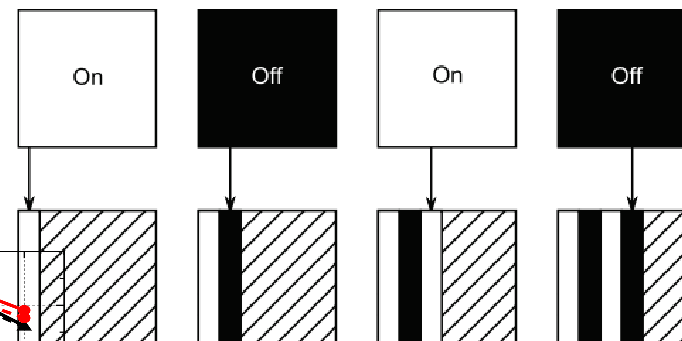


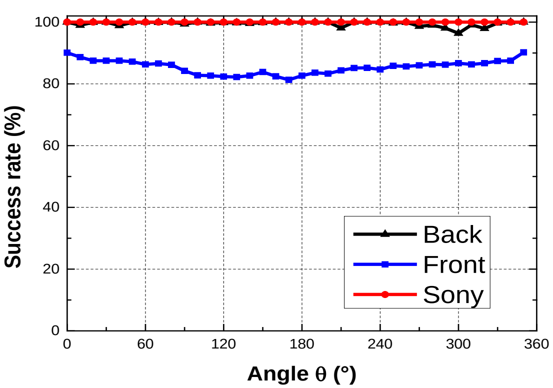
- FPGA-based digital pre-distortion waveform shaping scheme:
- Ideal for many application as part of
  - **Smart Environments**
  - **IoT**

VLC – D2DC for IoT

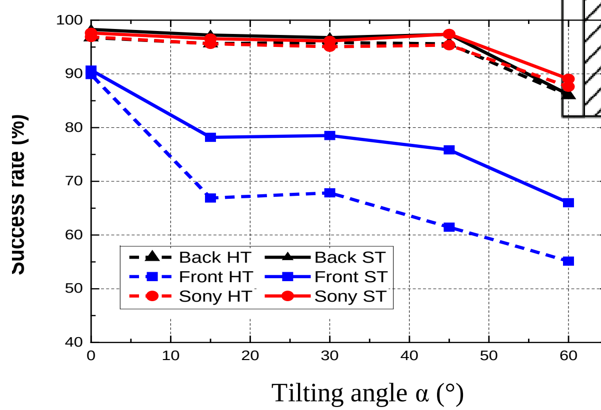
Smartphone VLC Communication

- Alternative to NFC for short range communications
- software based
- Android implementations
- **Rolling shutter - used in CMOS cameras for image capturing.** CMOS cameras capture rate: 20 - 30 frame





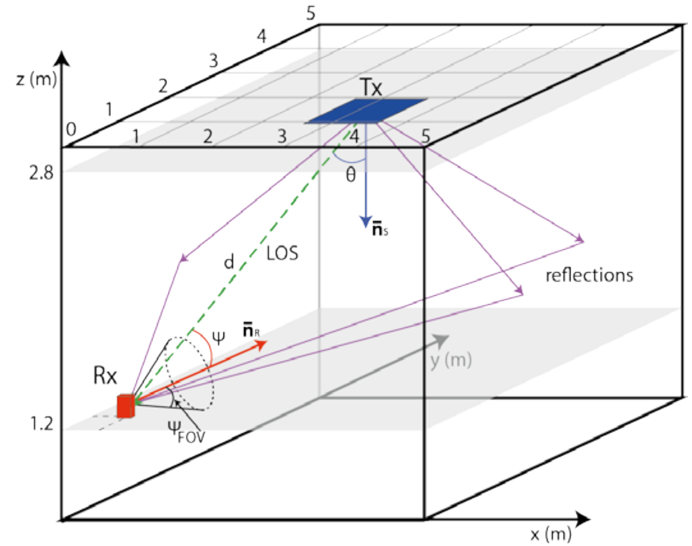
Bit success rate against rotation angle

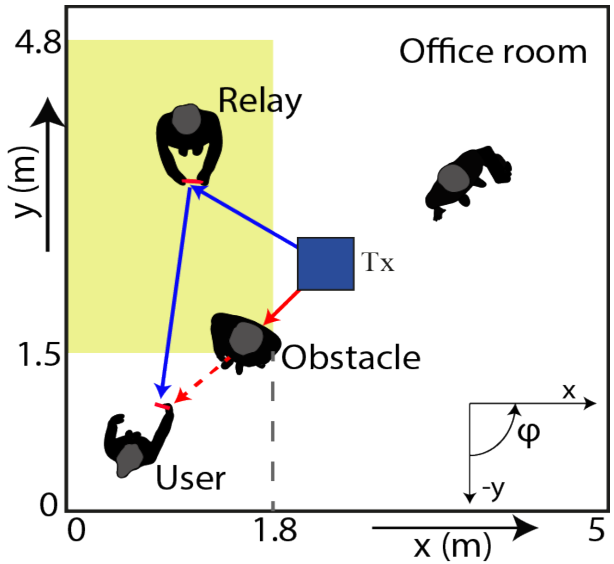


Bit success rate against tilting angle

Boubezari, R., Le Minh, H., **Ghassemlooy, Z.**, and Bouridane, A.: "Smartphone camera based visible light communication," J. of Lightwave Technology, 34 (17), pp. 4121-4127, Sept.1, 1 2016.

VLC – Relay Assisted

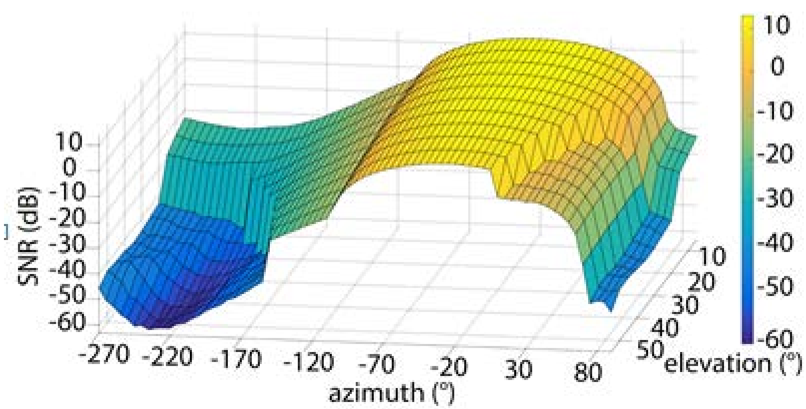


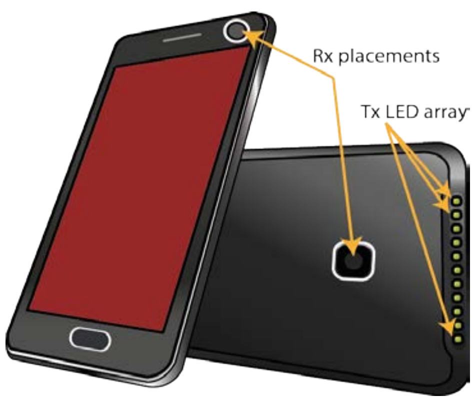


Based on observations of 1300 people using their MPs on the street, airports, on trains and buses:

- **49 % used MPs with only one hand**
- **90 % held it vertically facing upwards [1].**

Based on our own tests, people were reading messages and surfing the internet by holding MP typically with the elevation angle within the range of 5° - 65°.





[1] "How Do Users Really Hold Mobile Devices? :: UXmatters." [Online]. Available: http://www.uxmatters.com/mt/archives/2013/02/how-do-users-really-hold-mobile-devices.php. [Accessed: 02-Feb-2017].

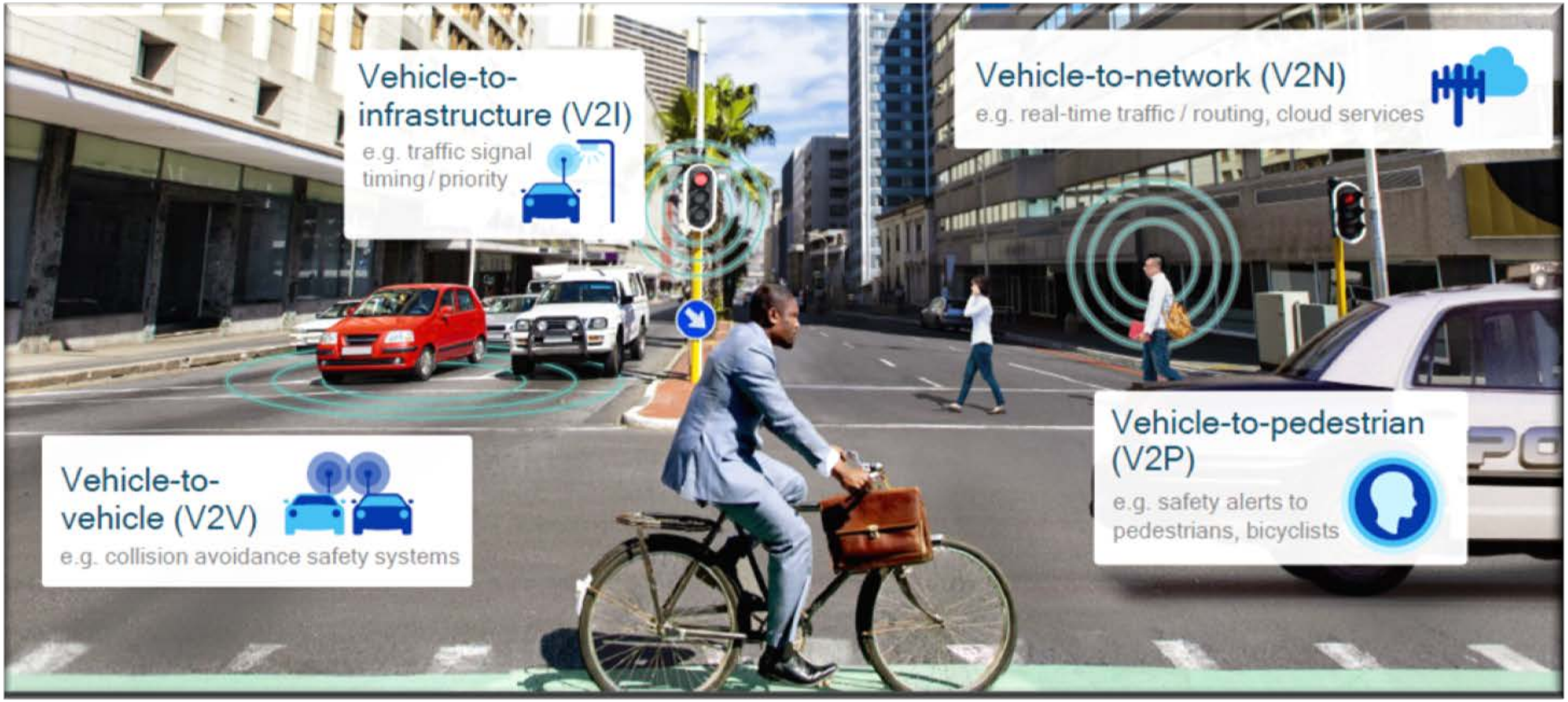
Mobile User Connectivity in Relay-Assisted Visible Light CommunicationsP Pešek, S Zvanovec, P Chvojka, MR Bhatnagar, Z Ghassemlooy, ... Sensors 18 (4), 1125

Project 5

VLC ITS

VisIon Projec - VLC for Intelligent Transportation

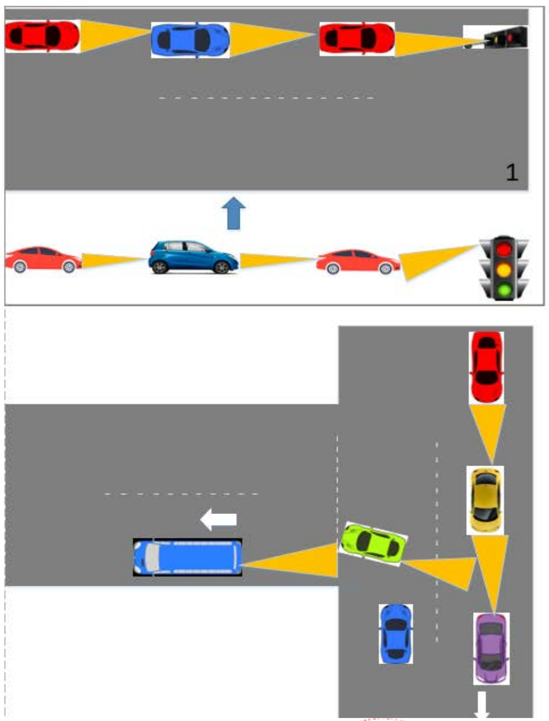
NU, UK, Tech. Univ. of Prague, Czech Rep., and Beijing Post and Telecommunications Univ, China

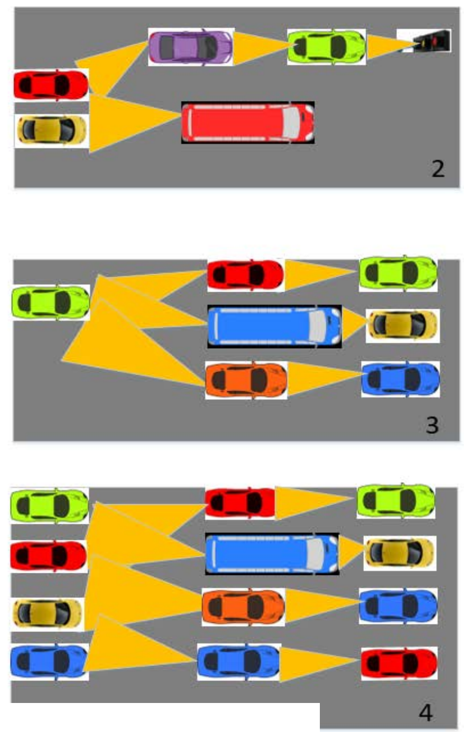


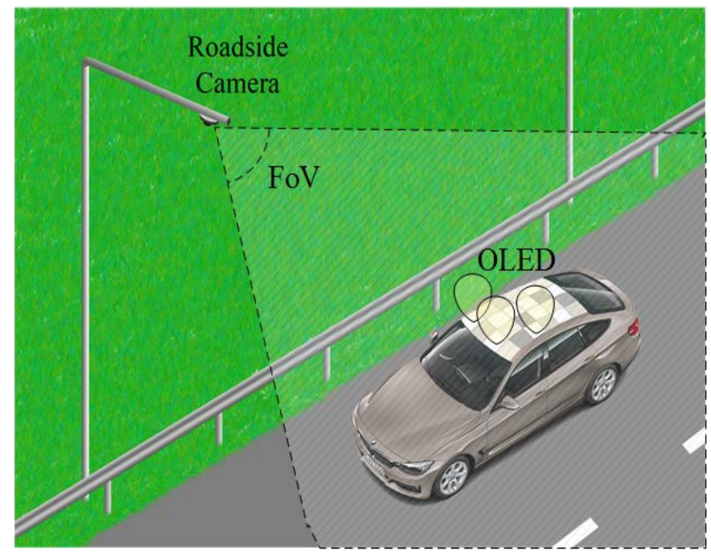
Gartner Research - forecast that new vehicles equipped with data connectivity will increase from 6.9 m/year in 2015 to 61 m/year in 2020.

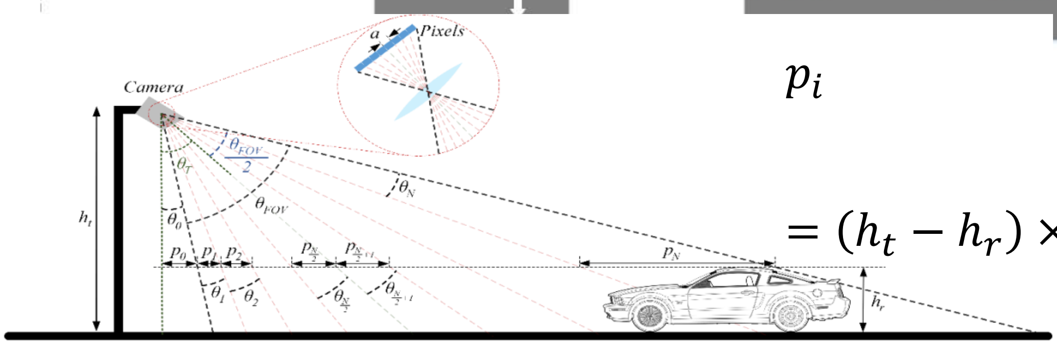
VisIon Projec - Multi-hop Vehicular Communications

Considering: SISO; SIMO; MISO and MIMO





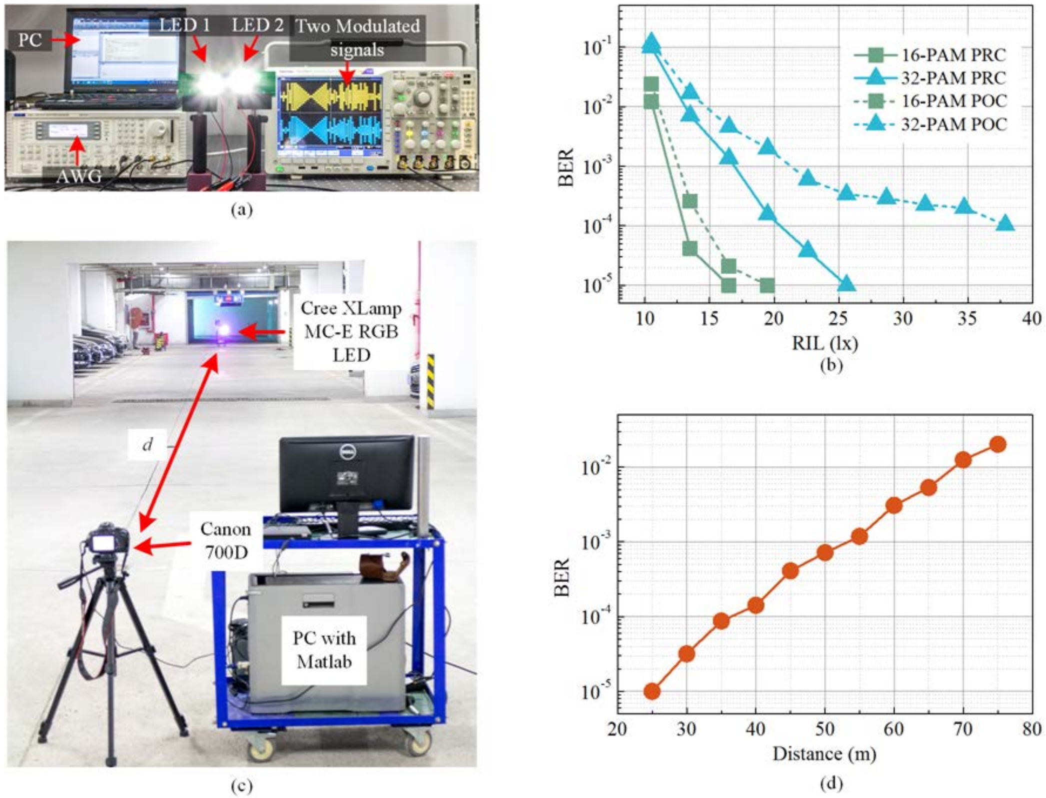




$$p_i = (h_t - h_r) \times \begin{cases} \tan(\theta_T + x_i) - \tan(\theta_T + x_{i-1}).\ i \le \dfrac{N}{2} \\ \tan(\theta_T + z_i) - \tan(\theta_T + z_{i-1}).\ i > \dfrac{N}{2} \end{cases}$$

VLC – Vehicular + Optical Camera Communications

NU, UK, Tech. Univ. of Prague, Czech Rep., and Beijing Post and Telecommun. Univ, China



Luo, P., Zhang, M., **Ghassemlooy, Z.**, Zvanovec, S., Feng, S., and Zhang, P.: "Undersampled-based modulation schemes for optical camera communications," in *IEEE Communications Magazine*, vol. 56, no. 2, pp. 204-212, Feb. 2018.

P. Luo, Z. Ghassemlooy, H. L. Minh, H. M. Tsai, and X. Tang, "Undersampled-PAM with subcarrier modulation for camera communications," in *Opto-Electronics and Communications Conference (OECC)*, 2015, pp. 1-3.

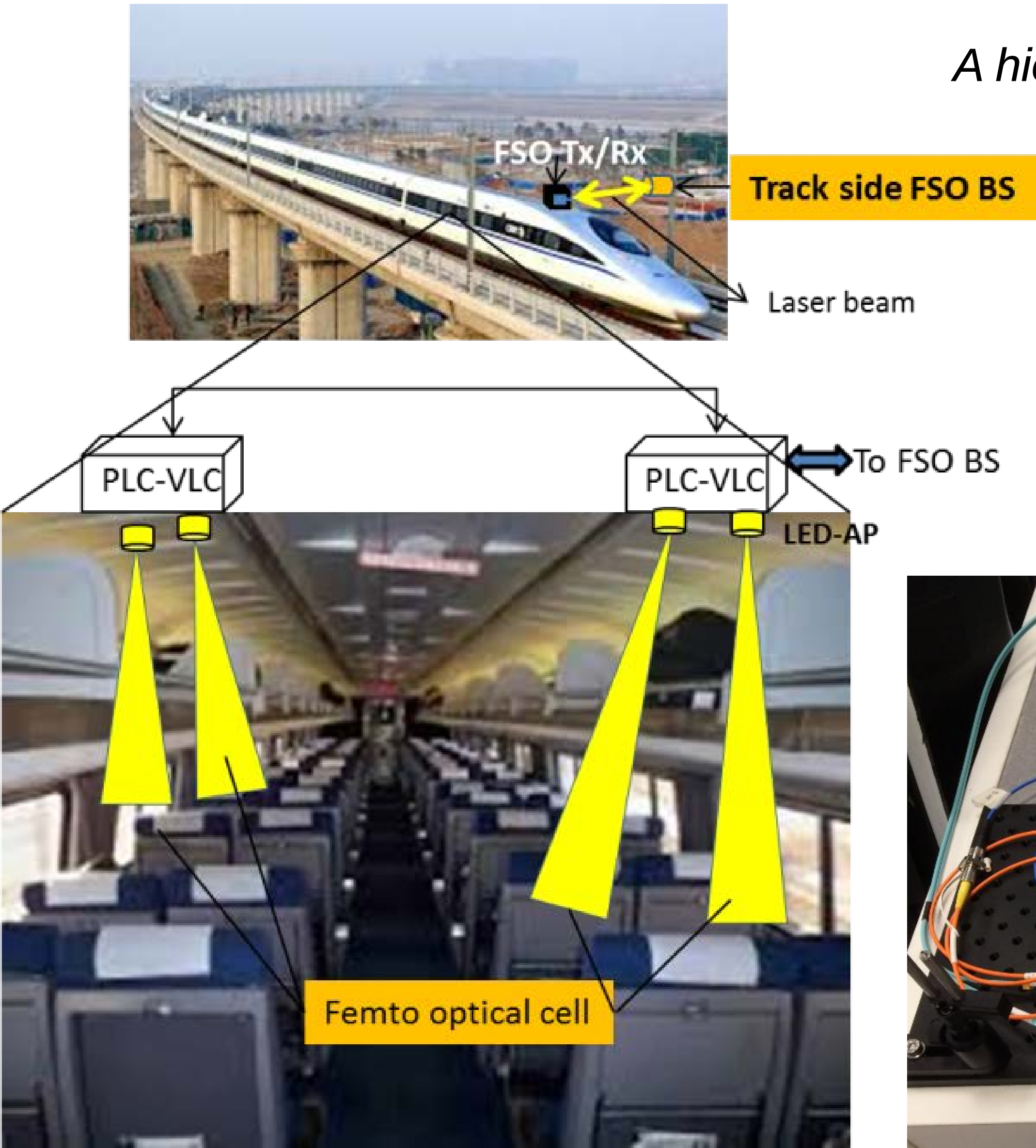
LUO, P., Ghassemloot, .Z, et al. Performance analysis of a car-to-car visible light communication system. *Applied Optics*. 2015, 54.7: 169-1706.

VLC – Long Distance OCC

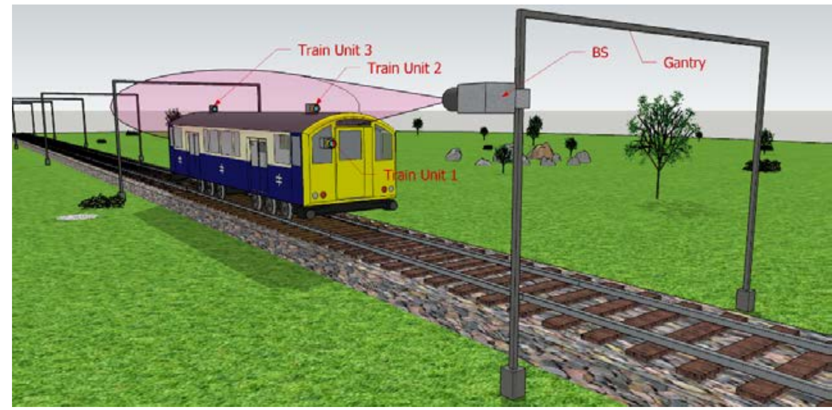
Technical University of Prague.

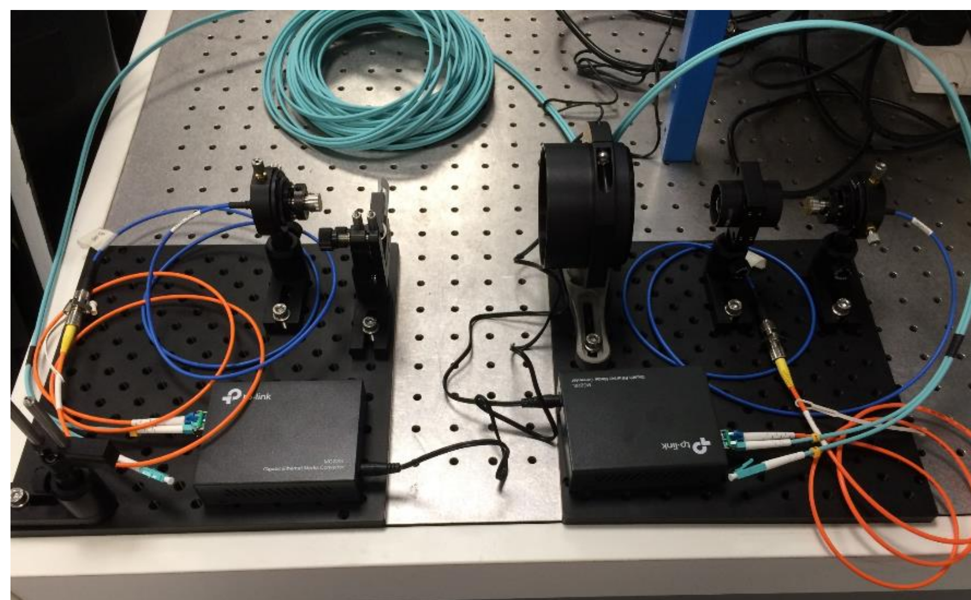
- Transmitter - A bright 40 COB-LED
- Receiver - a telescope camera composed of 2 concave mirrors with a narrow the field of view (FoV) of ~0.5º.
- Range of 150 m to 400 m.

VCL + FSO – Ground to Train (1-10 Gbps)

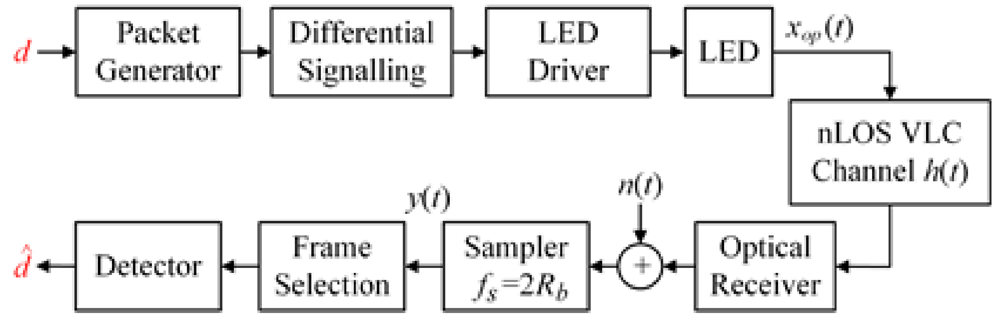


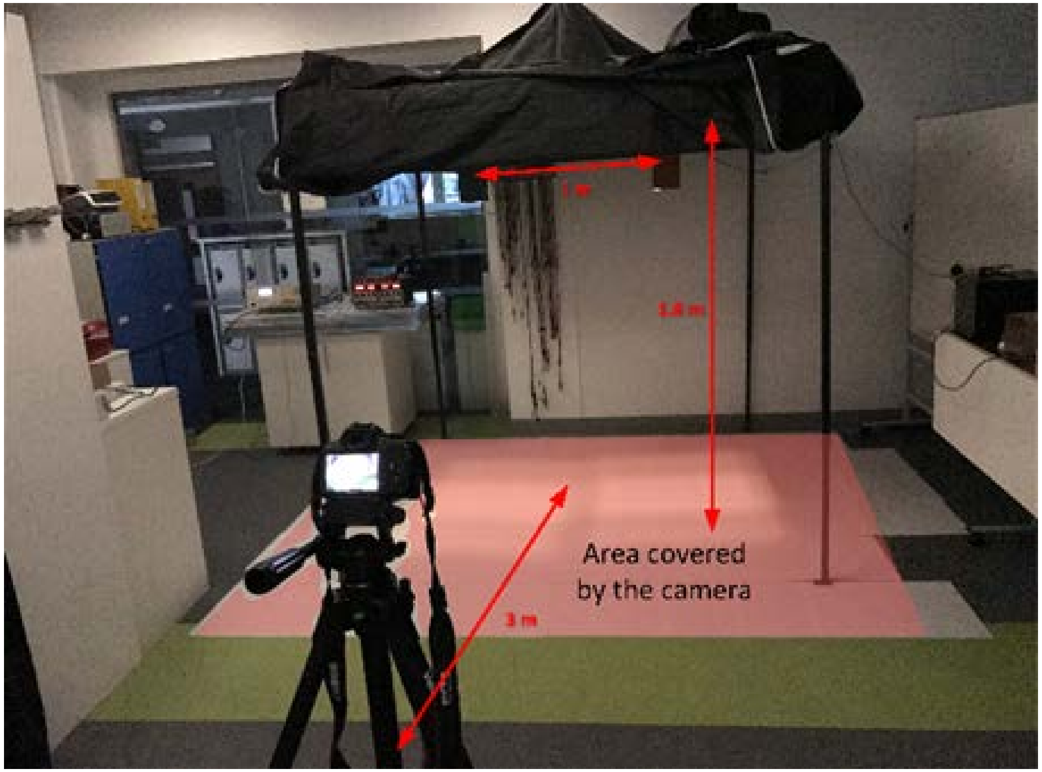
A hierarchical two-hop network structure

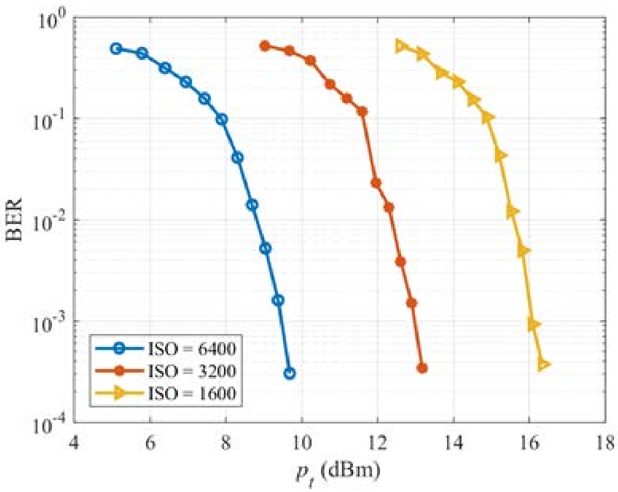




VLC – NLOS OCC for Smart Environment



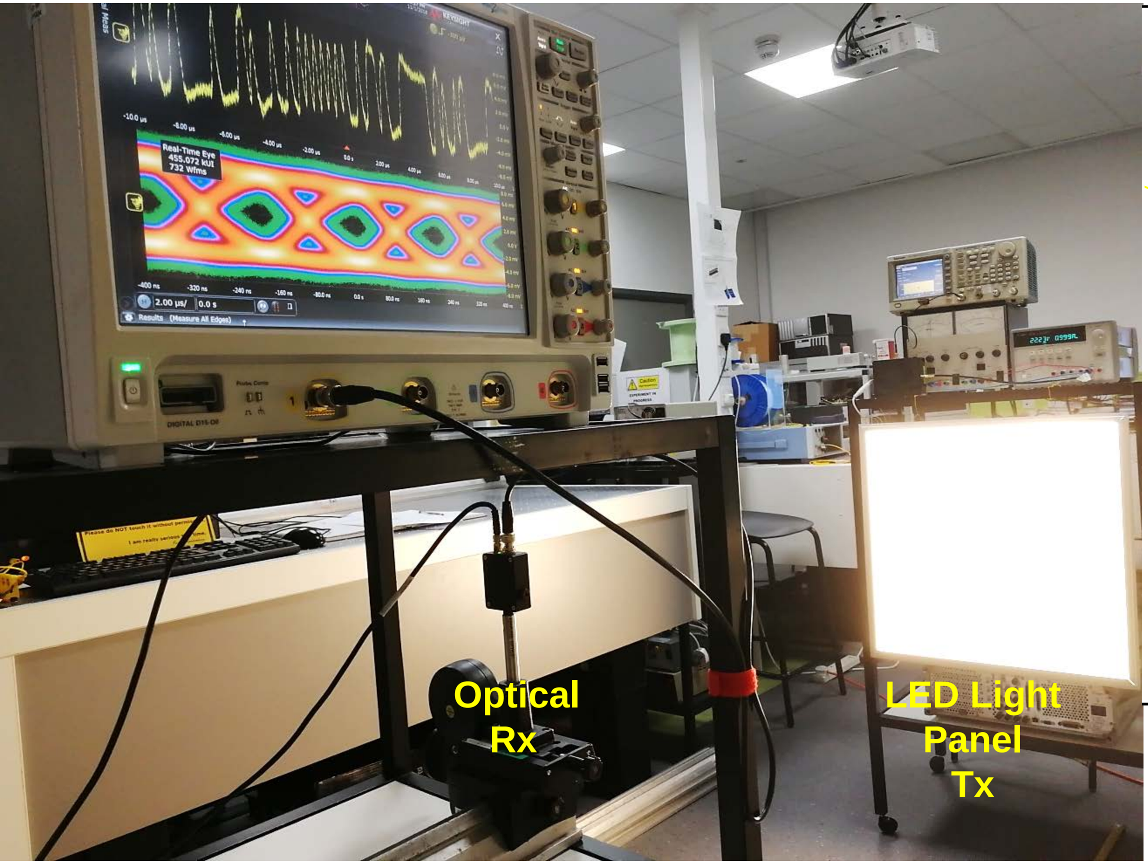




For different values of ISO,

Hassan, N. B., Ghassemlooy, Z., Zvanovec, S., Luo, P, and Le-Minh, H.: "Non-line-of-sight 2× N indoor optical camera communications," Applied Optics, 57 (7), pp. B144-B149, March 2018.

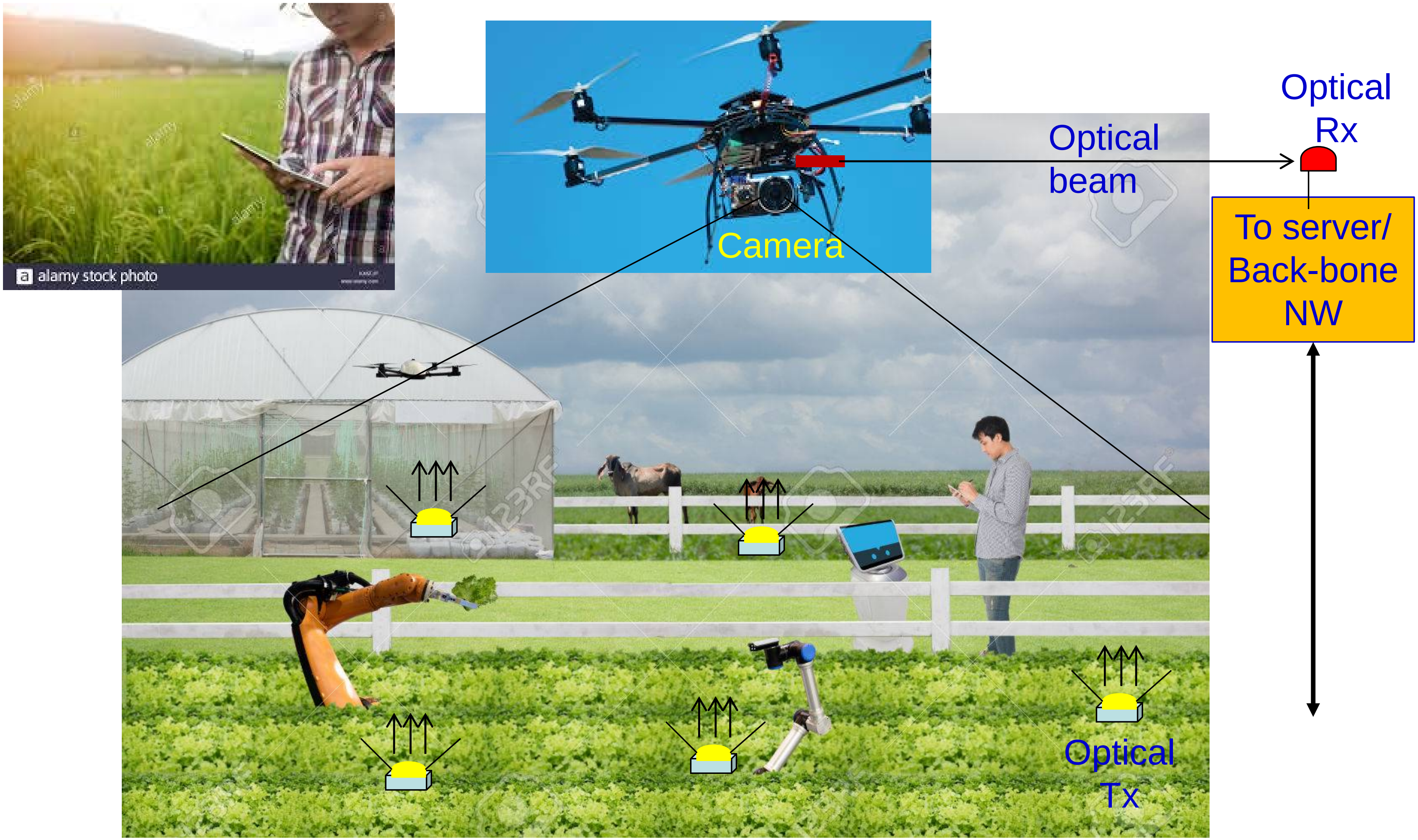
VLC – Diffuse LED Panel lighting



Data Rate	**> 5 Mb/s** OOK NRZ
Diffuse LED Panel	3900014-WW-EU, 1200 lm, 3000K, 0.6 x 0.6 m 192 LEDs, Beam angle 120º Bandwidth 400 kHz Illumination level 300 lux@1.5 m
Receiver	PIN Photodetector Tans-impedance amplifier
Distance	1.5 meter
Post-equalization	LMS adaptive equalizer

Future work – Neural network based equalizer

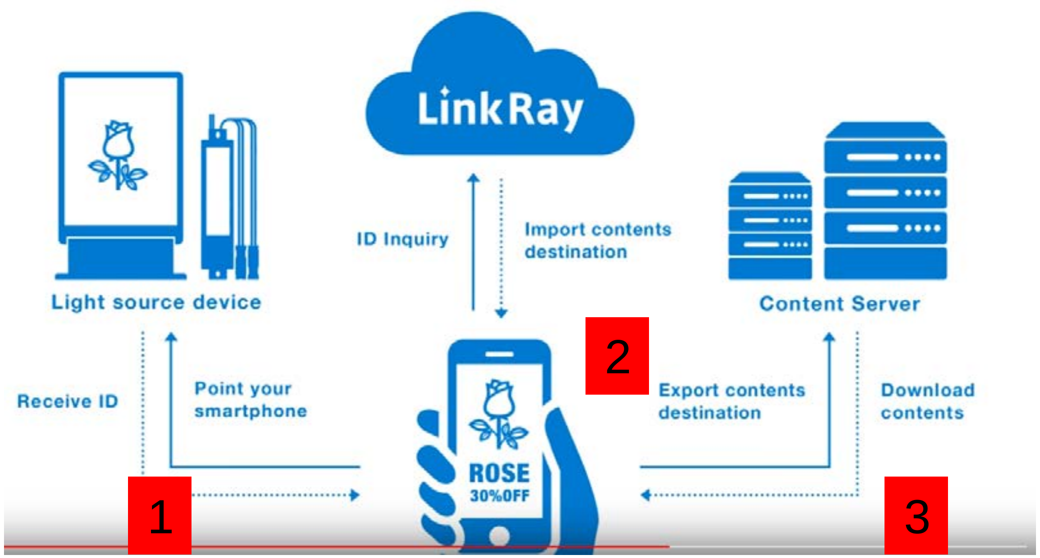
VCL + OCC - Smart Agriculture



Low data rate data transmission

VCL – Link Ray

Delivers mobile content using smartphones to read IDs sent from LEDs



Fast and Intuitive

Effective even in crowds

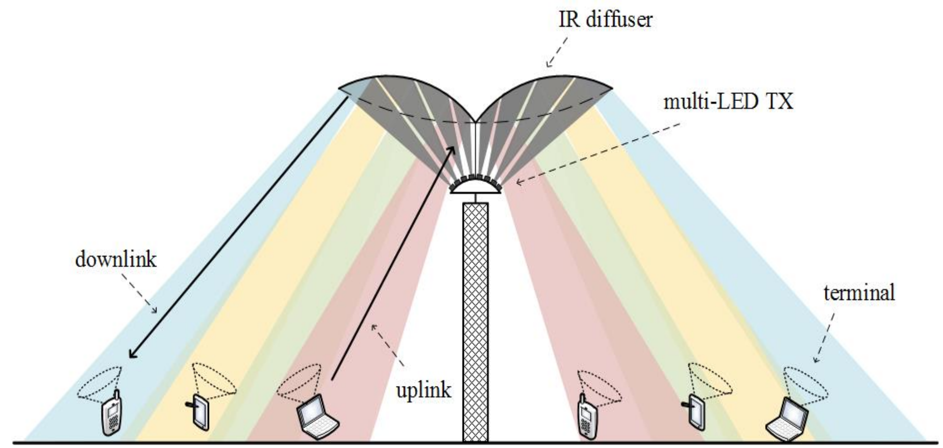
Effective in the distance if light reaches smartphone

https://www.youtube.com/watch?v=7IvuGXr3DPE Video

Northumbria University NEWCASTLE

OCRG

VCL – IOT - Optical Wireless for Outdoor Wireless Access



investigate the use of diffuse Infrared as the key technology of future (5G and beyond-5G) high-speed wireless access to the end-user in certain application areas (plazas, café, restaurants, sport venues, concert halls, train/bus station, airports, etc.), thus overcoming the critical problems of the continuously increasing RF spectrum congestion and interference scaling.

HELLENIC REPUBLIC
ARISTOTLE UNIVERSITY OF THESSALONIKI

infoscope hellas

ÖZYEĞİN ÜNİVERSİTESİ

Northumbria University NEWCASTLE

Fraunhofer Heinrich Hertz Institute

e-trikala

Wireless – Technology and Standards (short range)

Technology	Speed	Data Density
Wireless – Current		
WiFi (IEEE 802.11N)	150 Mbps	*
Bluetooth	3 Mbps	*
IrDa	4 Mbps	***
Wireless – Future		
Wi-Gig (IEEE 802.11ad)	2 Gbps @ 60 GHz; 10 m within a room	**
White WiFi (IEEE 802.11af & IEEE 802.11ah,	24 Mbps @54 and 790, 900 MHz	* (across huge areas a few km)
Giga-IR	1 Gbps	***
VLC	> 10 Gbps; a few meters within a room	****

VLC – Commercial World

LIGHTPOINTE

CVLC 中国可见光通信产业技术创新战略联盟 China Visible Light Communications Alliance

pureVLC™

PHILIPS

GE Lighting

intel

Supreme Architecture

CASIO

VLCC Visible Light Communications Consortium

infsoft smart connected locations

SIEMENS

VLC Ltd

Disney

RENESAS

COLOR KINETICS

LiFi Consortium

IEEE 802.15.7

Panasonic

eldoLED your product | our drive

SAMSUNG

Nakagawa Laboratories, Inc.

IBSENtelecom optical telecom designed with people in mind

LVX System

ByteLight

FIREFLY WIRELESS NETWORKS

VLCA Visible Light Communications Association 一般社団法人可視光通信協会

Outstanding Technology Co., Ltd.

NEC Corporation

Thomas Little, Boston University

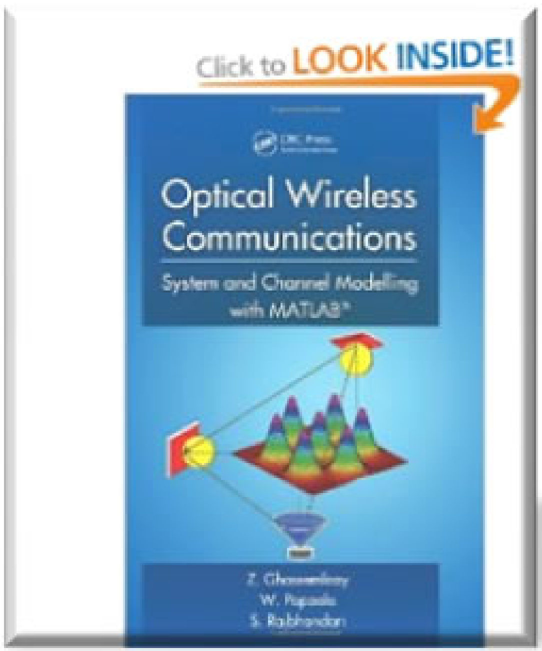
VLC – Final Comments

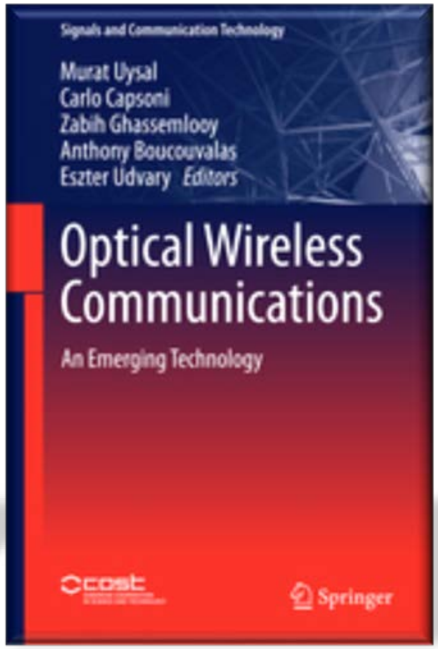
- A new revolution in wireless communications
- A complementary technology to RF
- Ideal for Smart environments

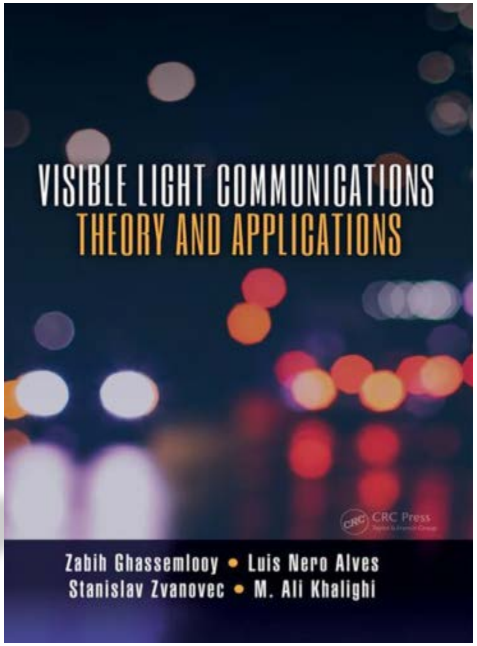
Future Challenges

LED bandwidth and nonlinearity
Coverage and distance
Dimming and no light
Blocking
Mobility
Uplink

Further Reading







Thank You.

Any Question?