VISIBLE LIGHT COMMUNICATIONS FOR THE IOT

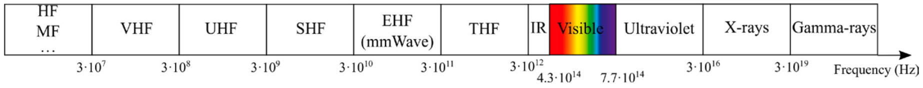
Borja Genoves Guzman

Maïté Brandt-Pearce

17th April 2023

University of Virginia

STORYLINE OF VISIBLE LIGHT COMMUNICATION

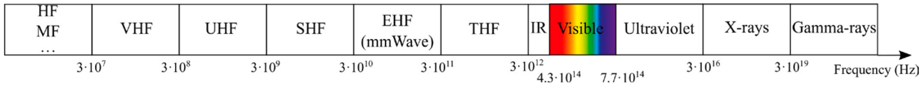


1800 1900 2000

Smoke signals
(900 BCE)

Source: wikipedia

STORYLINE OF VISIBLE LIGHT COMMUNICATION

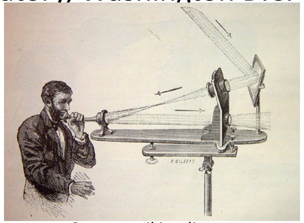


1800 1900 2000

Smoke signals
(900 BC)

Source: wikipedia

Photophone
Alexander Graham Bell (1880)
Bell´s laboratory, Washington D.C.

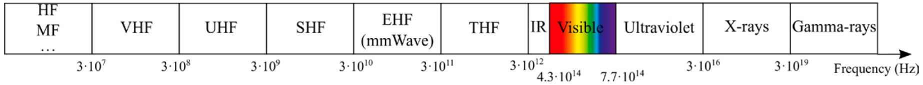


Source: wikipedia

Incandescent lamp
Thomas Edison (1880)

Source: youtube

STORYLINE OF VISIBLE LIGHT COMMUNICATION

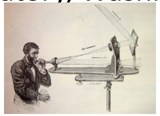


1800 1900 2000

Smoke signals
(900 BC)

Source: wikipedia

Photophone
Alexander Graham Bell (1880)
Bell´s laboratory, Washington D.C.



Source: wikipedia

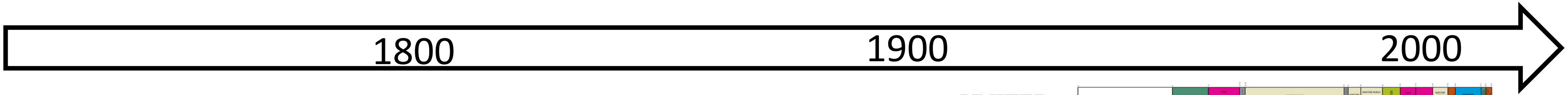
Incandescent lamp
Thomas Edison (1880)

Source: youtube

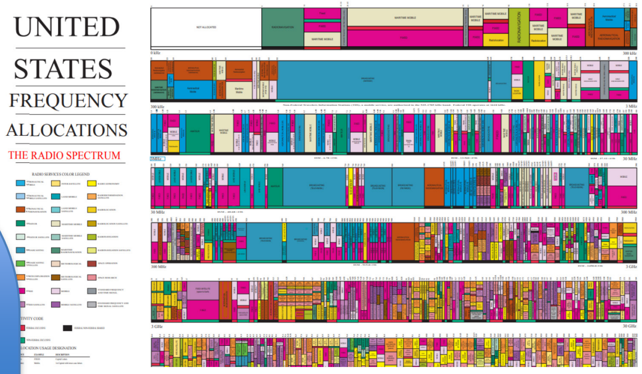
Radio, or wireless telegraph
Guglielmo Marconi (1890s)

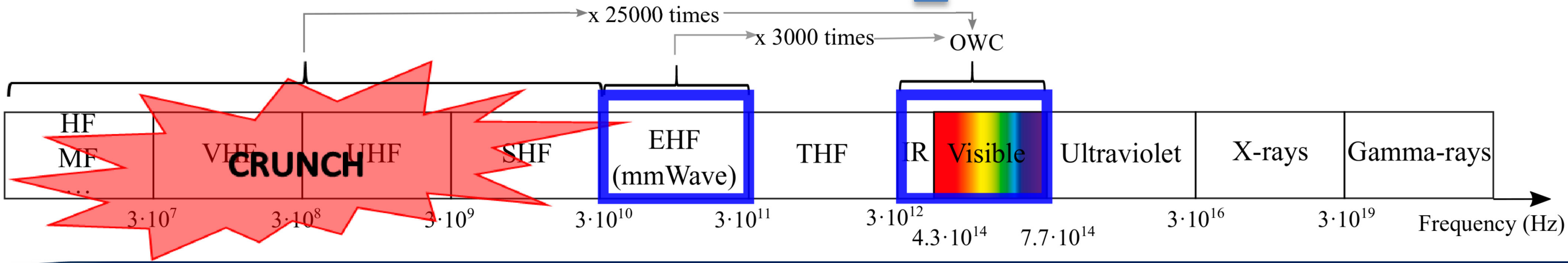
Source: UK Science Museum Group Collection

RADIO WIRELESS: A VLC STOPPER

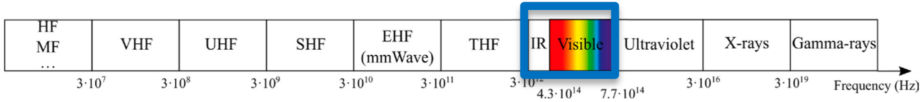


TV remote control





STORYLINE OF VISIBLE LIGHT COMMUNICATION

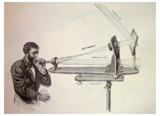


1800 — 1900 — 2000

Smoke signals
(900 BC)

Source: wikipedia

Photophone
Alexander Graham Bell (1880)
Bell´s laboratory, Washington D.C.



Source: wikipedia

Incandescent lamp
Thomas Edison (1880)

Radio, or wireless telegraph
Guglielmo Marconi (1890s)

Source: UK Science Museum Group Collection

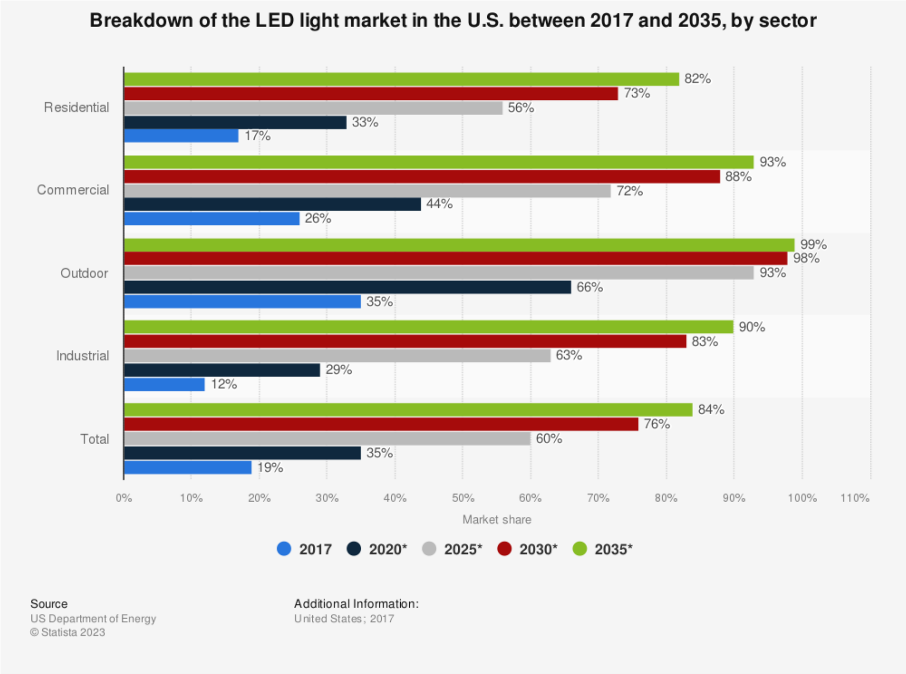
High-brightness blue LEDs
Shuji Nakamura (1993s)
NOBEL PRIZE in Physics in 2014

Lighting revolution:

- White LEDs
- High efficiency light sources (2% efficiency incandescent vs. 50% LED)
- x50 lifetime (>25k hours)

UNIVERSITY of VIRGINIA

U.S. LED LIGHT MARKET SHARE BY SECTOR 2017-2035



Source: US Department of Energy. (January 23, 2020). Breakdown of the LED light market in the U.S. between 2017 and 2035, by sector [Graph]. In Statista. Retrieved March 31, 2023, from https://www.statista.com/statistics/729435/led-light-market-distribution-in-the-us-by-sector/

University of Virginia

LEDS NOT ONLY FOR ILLUMINATION

- Illumination:
  - Energy savings
  - Good color rendering index
  - Low price and off-the shelf
  - …
- But LEDs can also be exploited to transmit information.
  - High modulation rates (hundreds of Mbps)
  - Higher security (propagation under controlled)
  - Large penetration market (infrastructure)
  - Larger bands
  - Unregulated frequency bands
  - New scenarios
  - …

Source: www.eng.ed.ac.uk

LINK BUDGET (EXERCISE)

Differently from RF technologies, VLC must comply with **both communication and illumination** requirements.

- Communication:

$P_{elec,rx} = (P_{opt} \cdot H \cdot n_{PD})^2 \rightarrow P_{elec,rx}\,[dBm] = 2 \cdot K - 40 \cdot log_{10} d$ (assuming a unitary n_{PD})

- Illumination:

$P_{opt,rx} = P_{opt} \cdot H \rightarrow P_{opt,rx}\,[dBm] = K - 20 \cdot log_{10} d$

Definitions:
$P_{elec,rx}$ = Electrical received power
P_{opt} = Optical transmit power
H = Channel gain $\propto 1/d^2$
d = distance between transmitter and receiver
n_{PD}= Photodiode responsivity [A/W]

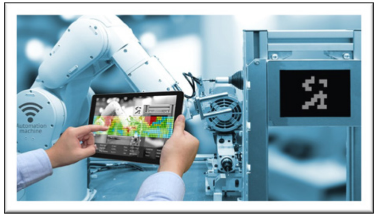
QUIZ 1

What is the maximum distance (d=0.1m; d=1m; d=10m; d=100m;) that we can achieve if:

- Receiver sensitivity = 0dBm
- Minimum illuminance required (in optical power) = 10dBm
- K = 20dBm

UNIVERSITY of VIRGINIA

USE CASES



Industry 4.0

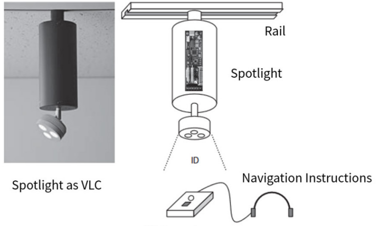
Smart building/ indoor applications

V2x communication

Hospitals

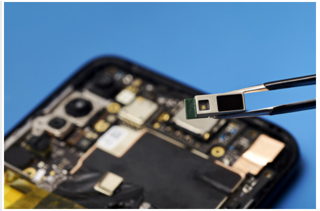
Nuclear power plants

SUCCESSFUL APPLICATIONS



TOSHIBA

Ford



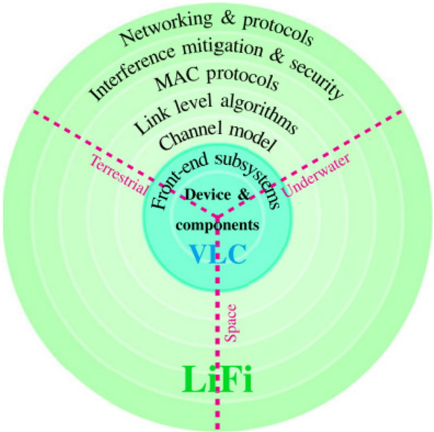
pureLiFi

Contents

1. VLC SYSTEM OVERVIEW

LIFI DEFINITION

- Point-to-point communication = Visible light communication (VLC)
- VLC in a networked system = LiFi

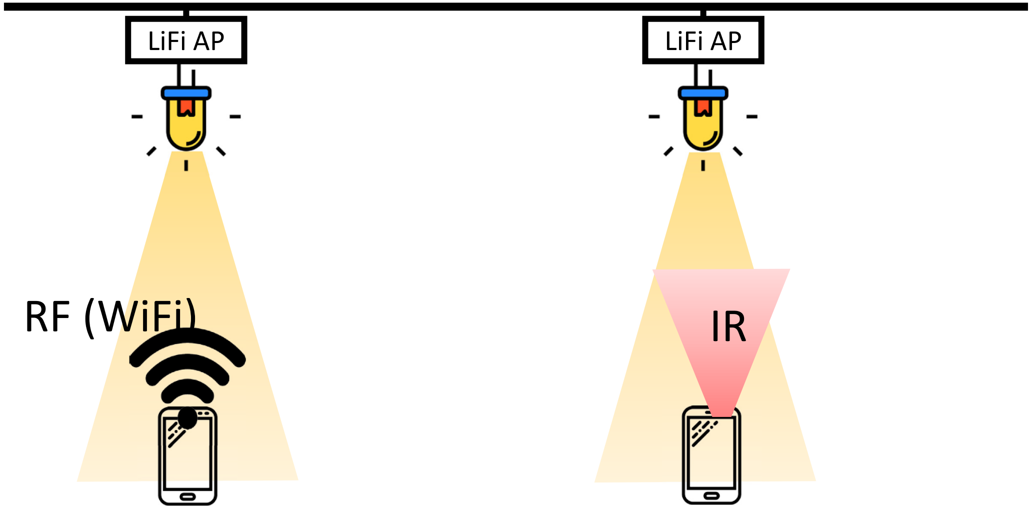


Source: H. Haas, L. Yin, Y. Wang and C. Chen, "What is LiFi?," in Journal of Lightwave Technology, vol. 34, no. 6, pp. 1533-1544, 15 March15, 2016.

UPLINK

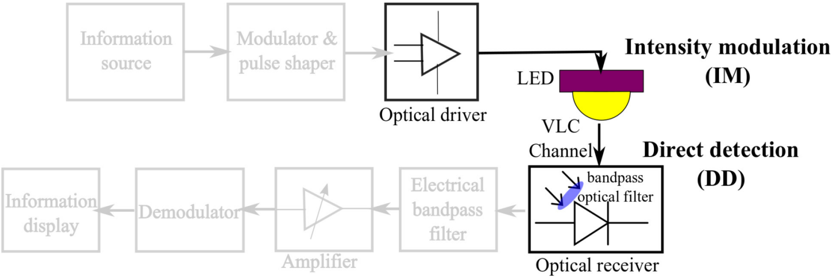
If LiFi is a networked system, it requires an uplink.

Candidates:



2. VLC HARDWARE

VLC BLOCK DIAGRAM



- **Intensity modulation (IM)** at the transmission: signal must be positive and real → Baseband transmission (TX and RX simpler than in RF).
- **Direct detection (DD)** at the reception: the receiver converts, proportionally, the detected received optical power into a photocurrent.

<u>Let's focus on the hardware employed in both the transmitter and the receiver:</u>

- Transmitter: Light-emitting diode (LED)
- Receiver: Photodiode (PD)

OUTLINE

- Transmitter: LEDs
  - Basic operation and types of LEDs
  - Properties of LEDs that are relevant for VLC
- Receiver: PDs
  - Basic operation and types of Photodiodes (PDs)
  - Properties of PDs that are relevant for VLC
- Additional materials for VLC
  - Polarizers, Retroreflectors

OUTLINE

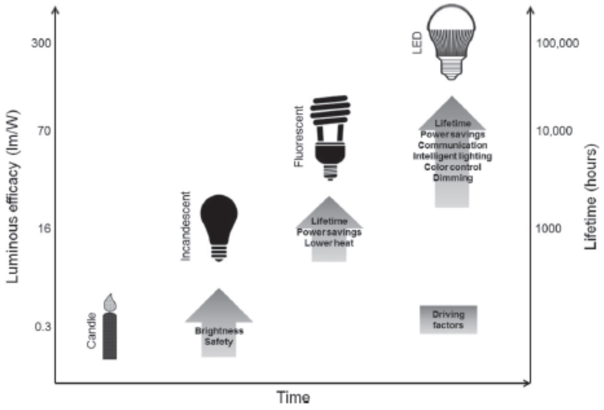
- **Transmitter: LEDs**
  - **Basic operation and types of LEDs**
  - **Properties of LEDs that are relevant for VLC**
- Receiver: PDs
  - Basic operation and types of Photodiodes (PDs)
  - Properties of PDs that are relevant for VLC
- Additional materials for VLC
  - Polarizers, Retroreflectors

TRANSMITTER IN VLC: LED

An LED is a solid state semiconductor device which has the capability of changing electrical energy into light energy. [1]

Why an LED is required for VLC and not traditional lighting technologies?

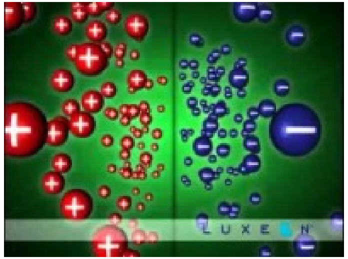
- Energy efficient
- Larger luminous efficacy
- Larger lifetime
- Free from hazardous substances such as mercury (fluorescent has mercury vapor)
- Capabilities for high speed modulation (tenths of MHz): baseband transmission
- Diversity of colour and intensity
- Price
- Most used and almost integrated in every environment.



Source: [1]

[1] D. Karunatilaka, F. Zafar, V. Kalavally and R. Parthiban, "LED Based Indoor Visible Light Communications: State of the Art," in IEEE Communications Surveys & Tutorials, vol. 17, no. 3, pp. 1649-1678, Thirdquarter 2015.

HOW DOES AN LED WORK?



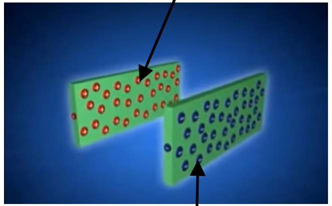
https://www.youtube.com/watch?v=BH9LI973H8w&t=15s

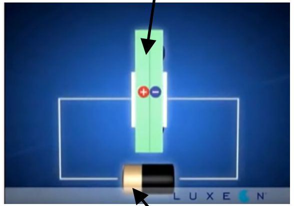
Source: Luxeon

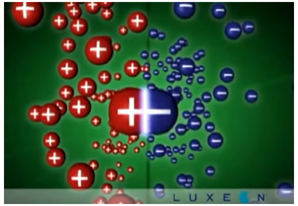
Electroluminiscence

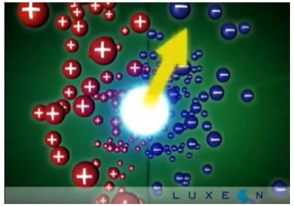
p-type semiconductor material (contains positively charged carriers = holes)

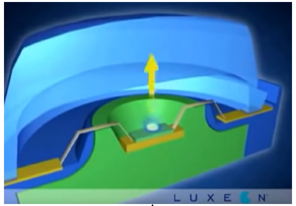
diode











battery

n-type semiconductor material (contains negatively charged carriers = electrons)

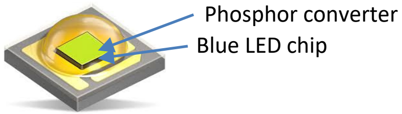
Positive and negative charges are forced to move in opposite directions

The chip is installed in a package that allows an electrical connection

Hole is at a lower energy level than electron. Electron must release energy to combine with holes = photon (unit of light)

TYPES OF LED

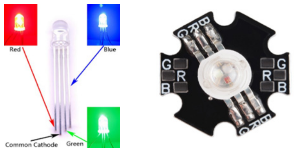
1) <u>Phosphor converted LED (pc-LED)</u>:



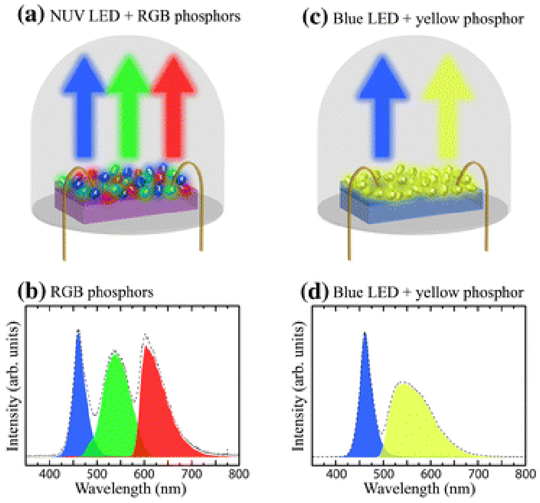
- Indium Gallium Nitride (InGaN) LED chip +
Yttrium Aluminum Garnet (YAG) phosphor coating.
- Depending on the amount of phosphor: warm-, neutral, cool-white.
- Pros: low complexity, price and good Color Rendering Index (CRI).

Anyone knows another way of transmitting white light?

2) <u>Multi-chip LED (RGB LED):</u>



- New modulation schemes: Colour-shift keying (CSK)
- Wavelength division multiplexing (WDM)
- Pros: higher bandwidth.



Source: [2]

[2] Yuan-Chihand Karlsson Lin and Marco Mathsand Bettinelli, “Inorganic Phosphor Materials for Lighting,” Topics in Current Chemistry, vol. 374, no. 2, Apr. 2016.

TYPES OF LED

3) <u>Organic light emitting diode (OLED):</u> use of an organic layer between positive and negative carriers.

- Lower bandwidth than inorganic LEDs.
- Lower lifetime than inorganic LEDs.

4) <u>Micro LEDs (μLED):</u> AlGaN-based micro-light.

- Large bandwidths (~400 MHz) due to low capacitance in LEDs.

Both are typically used for flat panel displays.

Currently: a large amount of LED types, useful for different application and scenarios.

There is an influence between semiconductor material and emitted colour:

Semiconductor Material	Wavelength	Color
GaAs - Gallium Arsenide	850-940nm	Infra-Red
GaAsP - Gallium Arsenic Phosphide	630-660nm	Red
GaAsP - Gallium Arsenic Phosphide	605-620nm	Amber
GaP - Gallium Phosphide	585-595nm	Yellow
InGaAIP - Indium Gallium Aluminum Phosphide	550-570nm	Green
SiC - Silicon Carbide	430-505nm	Blue
GaN - Gallium Nitride	450nm	White

Source: [3]

[3] L. E. M. Matheus, A. B. Vieira, L. F. M. Vieira, M. A. M. Vieira and O. Gnawali, "Visible Light Communication: Concepts, Applications and Challenges," in *IEEE Communications Surveys & Tutorials*, vol. 21, no. 4, pp. 3204-3237, Fourthquarter 2019.

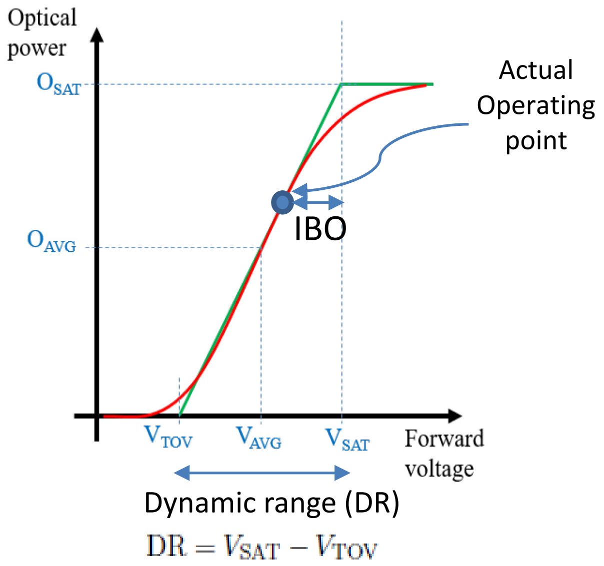
PROPERTIES OF LED THAT ARE IMPORTANT FOR VLC

- **LED is a current(or voltage)-driven device:**

The output optical power is linearly proportional to the forward current $I(t)$ by means of the **electrical-to-optical (E/O) conversion efficiency of the LED** η_{led} as

$$P_{\text{opt}} = \eta_{\text{led}} \cdot E\{I(t)\}$$

- **Non-linear LED's transfer function**



The input real signal must be scaled (α) and biased (B_{DC}) to make it work within the DR as

The α and B_{DC} values determine the input back-off (IBO)

Be careful with peak-to-average power ratio (PAPR) of input signals.

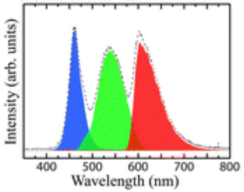
PROPERTIES OF LED THAT ARE IMPORTANT FOR VLC

- **White color for illumination**

Planckian locus defines the possible Correlated Color Temperature (CCT) points in the CIE 1931 diagram perceived as a white color by humans.

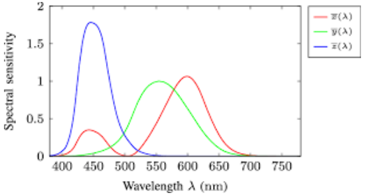
CCT defines the appearance of a white light. CCT ∈ {2000K (warm white), 6500K (cool white)}

How the CIE 1931 points are computed?



Power spectral density of LED P(λ)

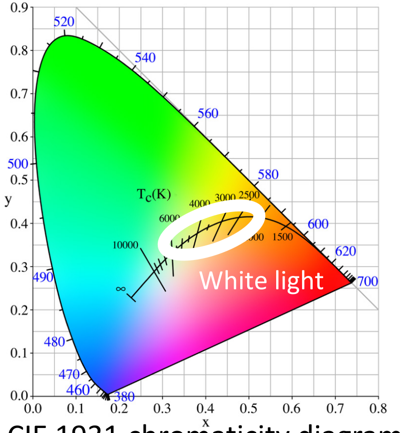
*



Color matching functions: chromatic response of the observer (average human's chromatic response) $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$

$$X = \int_{\lambda} \bar{x}(\lambda) P(\lambda) d\lambda$$
$$Y = \int_{\lambda} \bar{y}(\lambda) P(\lambda) d\lambda$$
$$Z = \int_{\lambda} \bar{z}(\lambda) P(\lambda) d\lambda$$

$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z}$$



CIE 1931 chromaticity diagram

OUTLINE

- Transmitter: LEDs
  - Basic operation and types of LEDs
  - Properties of LEDs that are relevant for VLC

- **Receiver: PDs**
  - **Basic operation and types of Photodiodes (PDs)**
  - **Properties of PDs that are relevant for VLC**

- Additional materials for VLC
  - Polarizers, Retroreflectors

RECEPTION IN VLC

- The receiver in a VLC system is in charge of **capturing light and converting it into electrical current.**

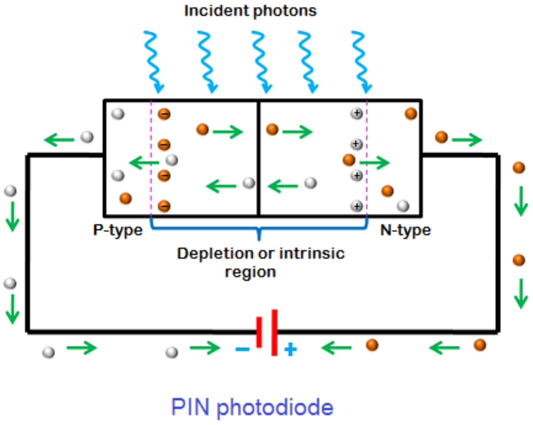
- Typically, a **photodiode (PD)** is used as receiver in a VLC system, but some other receivers may be used.

Anyone knows other devices to perform as VLC receivers?

University of Virginia

HOW DOES A PD WORK?

- A **PD is a diode operating in reverse bias** (since photocurrent generated is in the order of (≈) diode current range and we can easily identify the change in diode current due to the impinging illumination).
  - Differently, if the diode operates in forward bias, Diode current >> photocurrent and we cannot detect the current changes due to illumination.



Source: [4]

The charge carriers from *p* and *n* semiconductors are stored in the intrinsic semiconductor until an equilibrium point is reached → Photocurrent is created

[4] www.physics-and-radio-electronics.com

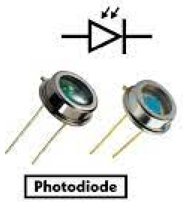
TYPES OF RECEIVERS IN VLC

- PD [5]
  - PIN PD:
    - p-type semiconductor + undoped intrinsic semiconductor + n-type semiconductor
    - Responsivity: in the range of 0.2 and 0.4 A/W.
    - Achievable 3-dB bandwidth is around hundreds of MHz and even GHz

  → Suitable for environments with relatively high light intensity

  - Avalanche PD (APD):
    - A high current gain due to an impact ionization when applying a high reverse bias voltage.
    - Responsivity: typically higher than unity.
    - Extra noise and it is sensitive to temperature changes.

  → Suitable for weak incident light intensity



[5] H. Elgala, R. Mesleh and H. Haas, "Indoor broadcasting via white LEDs and OFDM," in *IEEE Transactions on Consumer Electronics*, vol. 55, no. 3, pp. 1127-1134, August 2009.

TYPES OF RECEIVERS IN VLC

- LED [6]:
  - They have photo-sensing characteristics.
  - Detects reduced wavelength range $\rightarrow$ May reduce interference and noise.
  - May simplify a bi-directional deployment (only one element at each extreme).
- Image sensors (cameras) [7]:
  - Image sensors can spatially separate light sources $\rightarrow$ Multiplexing techniques not required.

- Solar panels [8]
  - Communication + energy harvesting is possible.

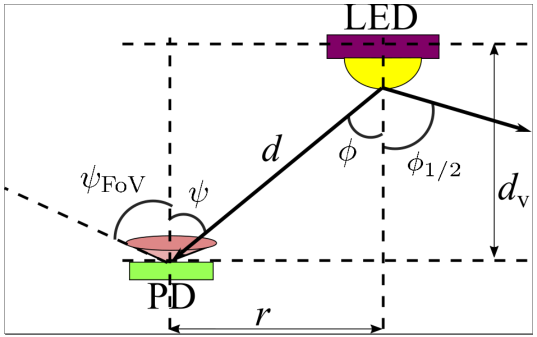
[6] D. Giustiniano, N. O. Tippenhauer and S. Mangold, "Low-complexity Visible Light Networking with LED-to-LED communication," *2012 IFIP Wireless Days*, Dublin, 2012, pp. 1-8.
[7] I. Takai, S. Ito, K. Yasutomi, K. Kagawa, M. Andoh and S. Kawahito, "LED and CMOS Image Sensor Based Optical Wireless Communication System for Automotive Applications," in *IEEE Photonics Journal*, vol. 5, no. 5, pp. 6801418-6801418, Oct. 2013, Art no. 6801418.
[8] Z. Wang, D. Tsonev, S. Videv and H. Haas, "On the Design of a Solar-Panel Receiver for Optical Wireless Communications With Simultaneous Energy Harvesting," in *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 8, pp. 1612-1623, Aug. 2015.

PROPERTIES OF PD THAT ARE IMPORTANT FOR VLC

Photocurrent generated by the PD is proportional to the received optical power

$$I_{\text{photocurrent}} = \eta_{\text{pd}} P_{\text{opt,rx}}$$

where η_{pd} is the PD's responsivity.



Extra elements used at the receiver:

- **Optical concentrator**.

- **Filter**: to eliminate signals out of the desired band.
  - Typically it costs an extra loss G_f due to absorption and reflection phenomena.

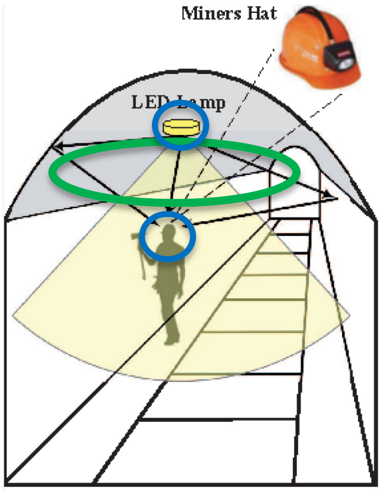
UNIVERSITY of VIRGINIA

HOW DO THE FRONT-END DEVICES AFFECT TO THE END-TO-END CHANNEL?

Received signal: $y(t) = x(t) \otimes \mathbf{h(t)}$

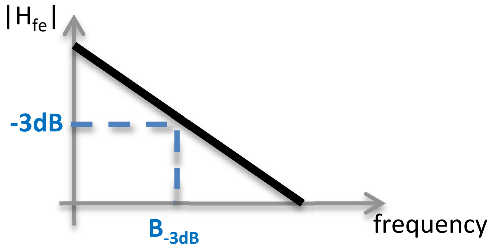
Optical wireless communication channel:

$$h(t)=h_{fe}(t)\otimes h_{fs}(t) \xrightarrow{FT} H(f)=H_{fe}(f)\,H_{fs}(f)$$

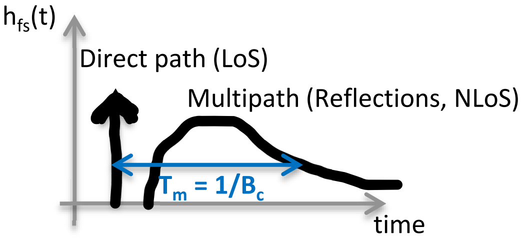


J. Wang, et al., "A new VLC channel model for underground mining environments," IWCMC, Valencia, Spain, 2017.

Front-end elements channel



Free-space channel



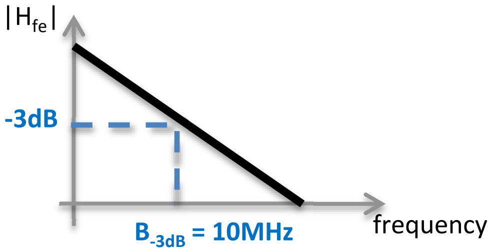
B_c=coherence bandwidth, i.e., range of frequencies where the bandwidth is considered flat

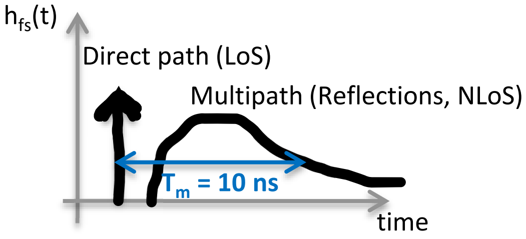
UNIVERSITY of VIRGINIA

QUIZ 2

We have a VLC system with the following front-end and free-space channels.

Which element is limiting the system bandwidth?





NOISE SOURCES (COMMONLY MODELED AS AN AWGN)

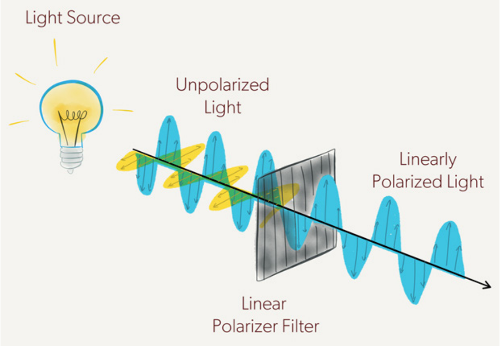
- Shot noise: Produced by the fluctuation in number of photons that arrive to the destination.
- Thermal noise: Produced by the thermal agitation of electrons in the resistive units at the receiver.
- Clipping noise: Produced by sending samples out of the LED's dynamic range (be careful with PAPR in multicarrier modulation schemes).
- (Interference from other APs)

OUTLINE

- Transmitter: LEDs
  - Basic operation and types of LEDs
  - Properties of LEDs that are relevant for VLC
- Receiver: PDs
  - Basic operation and types of Photodiodes (PDs)
  - Properties of PDs that are relevant for VLC
- **Additional materials for VLC**
  - **Polarizers, Retroreflectors**

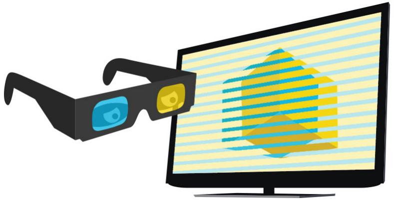
ADDITIONAL MATERIALS FOR VLC

- <u>Polarizers</u>:
  - Light, by default, is completely unpolarized.
  - Applications: Transmit and receive data in specific polarization, reduce interference…



Source: photopills.com

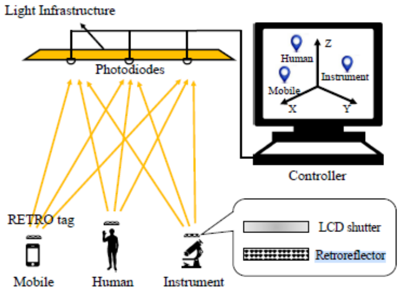
Polarized 3D system (cinema)



ADDITIONAL MATERIALS FOR VLC

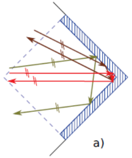
- <u>Retroreflector:</u>
  - Typically used in safety reflective signals in automotive:

  - Light-wave device that reflects the incoming light with a minimal scattering.
  - A backward channel can be made by using a retroreflector in every IoT device.
  - If a liquid crystal display (LCD) is installed, a unique ID can be reflected.

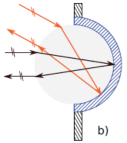


Source: [9]

  - Types (among others):



Corner-cube retroreflector [10]



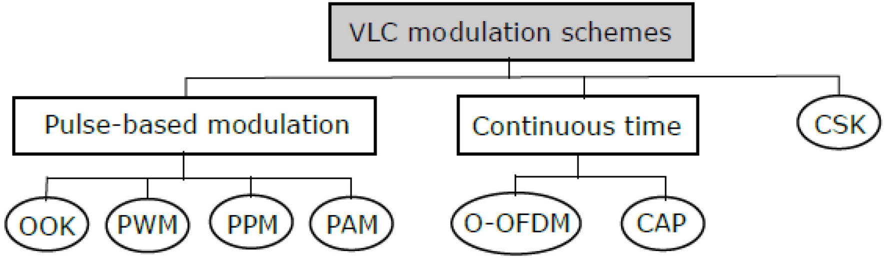
Spherical retroreflector (cat's eye) [10]

  - Applications: Positioning systems (RSSI + trilateration), backward channel with low data rate (IoT), passive communications, etc.
  - **Passive VLC:** transmitter (**mirrors or LC shutter**) allows much energy savings:
    - **Passive** consumes **hundreds of uW** vs. **active** transmissions (WiFi, ZigBee, BLE, LoRa, NB-IoT…) in the order or **hundreds of mW.**

[9] S. Shao, A. Khreishah and I. Khalil, "Enabling Real-time Indoor Tracking of IoT Devices Through Visible Light Retroreflection," in *IEEE Transactions on Mobile Computing*, 2019.
[10] L. Janik, M. Novak, A. Dobesch and L. Hudcova, "Retroreflective optical communication," in *Proc. 2017 Conference on Microwave Techniques (COMITE)*, Brno, 2017, pp. 1-4.

3. PHY LAYER: VLC MODULATION SCHEMES

MAIN MODULATION SCHEMES IN VLC



- On-Off-Keying (OOK)
- Pulse-Width Modulation (PWM)
- Pulse Position Modulation (PPM)
- Pulse Amplitude Modulation (PAM)

- Optical Orthogonal Frequency Division Multiplexing (O-OFDM)
- Carrier-less Amplitude and Phase modulation (CAP)

- Color Shift Keying (CSK)

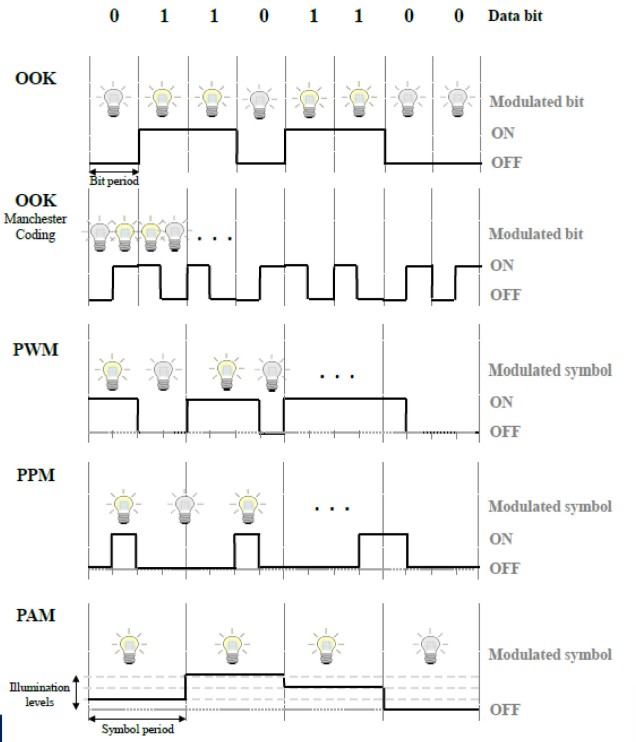
PULSE-BASED MODULATION SCHEMES

- On-Off-Keying (OOK)

- Pulse-Width Modulation (PWM)

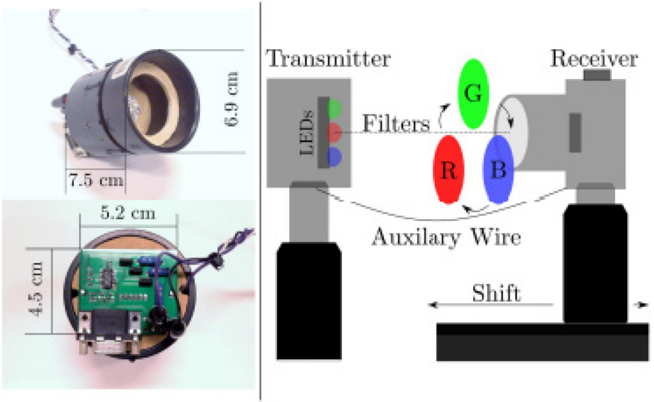
- Pulse Position Modulation (PPM)

- Pulse Amplitude Modulation (PAM)

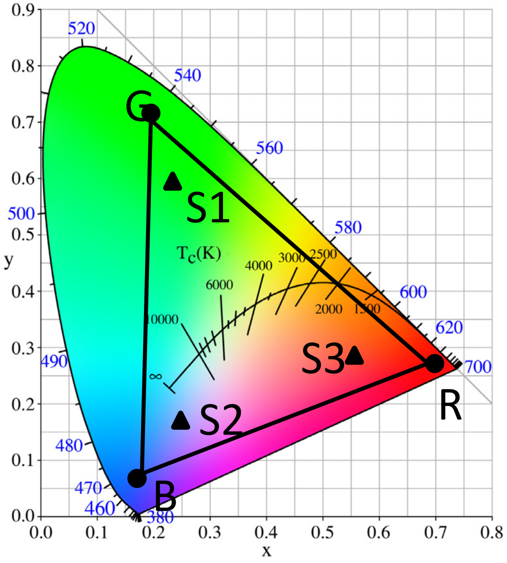


UNIVERSITY of VIRGINIA

COLOR SHIFT KEYING IN VLC



Source: E. Monteiro and S. Hranilovic, "Design and Implementation of Color-Shift Keying for Visible Light Communications," in Journal of Lightwave Technology, vol. 32, no. 10, pp. 2053-2060, May15, 2014.



CIE 1931 chromaticity diagram

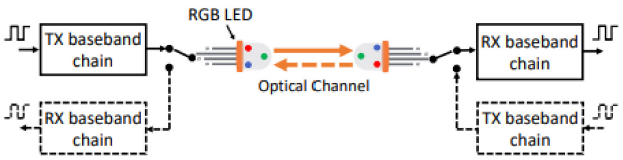
UNIVERSITY of VIRGINIA

4. VLC FOR IOT

KEY FEATURES FOR IOT

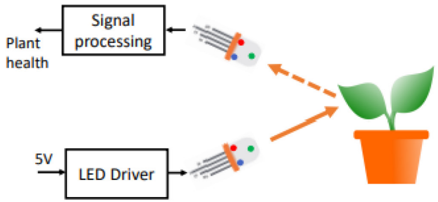
- Light Emitting Diodes (LEDs) are driving a revolution in lighting systems.
- Entering the Internet of Things (IoT) market with **embedded sensory functionalities**.
- Visible Light Communication (VLC) → LED revolution with the language of **ubiquitous networks**.
- IoT systems can leverage the **low baseline energy consumption of LEDs** to jointly deliver **lighting and networked communication**.

Multifunctionality of RGB LEDs for IoT:



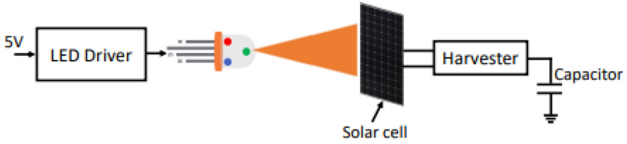
(a) RGB LED bulb as VLC transmitter and receiver.

a) Communication



(b) RGB LED bulb to sense environmental parameters.

b) Sensing



(c) RGB LED bulb to optimize energy harvesting.

c) Energy harvesting.

Source: M. S. Mir, B. Majlesein, B. G. Guzman, J. Rufo and D. Giustiniano, "RGB LED Bulbs for Communication, Harvesting and Sensing," 2022 IEEE International Conference on Pervasive Computing and Communications (PerCom), Pisa, Italy, 2022, pp. 180-186.

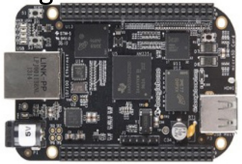
PROTOTYPING VLC FOR IOT

A summary of state-of-the-art VLC platforms and implementations:

http://www.openvlc.org/

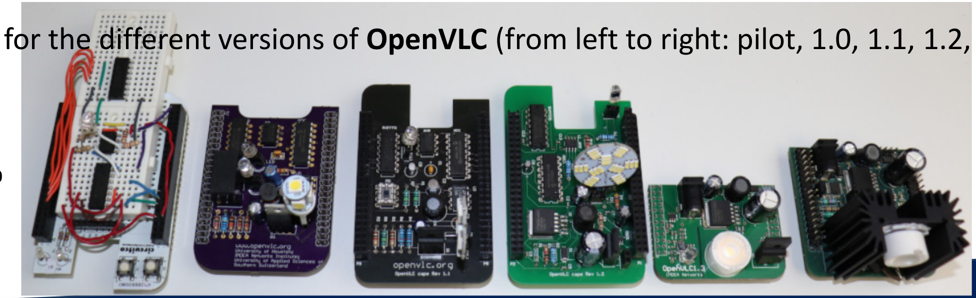
Name	Optical TX antenna	Optical RX antenna	Processor	Data rate	Distance	Open source	TCP/IP support	Commercial product
OpenVLC 1.4	XHP35A	SFH206K	BBB	1 Mb/s (400 kb/s)	19 m	Yes	Yes	No
Shine [3]	HLMP-CMTA-450DD	SFH203P	Arduino	1 kb/s	1 m	Yes	No	No
EnLighting [4]	SoC bulb	SoC PDs	Arduino	400 b/s	5 m	No	Yes	No
SynLight [5]	LUXEON 3014	SD3421	MSP430F2618	60 kb/s	70 cm	No	No	No
SmartVLC [6]	Philips 4.7W LED	SFH206K	BBB	100 kb/s	3.6 m	Yes	No	No
DenseVLC [7]	CREE XT-E	S5971	BBB	33.9 kb/s	4 m	Yes	Yes	No
Purple VLC [8]	5mm LEDs	SFH213	BBB	100 kb/s	6 m	Yes	No	No
modBulb [9]	unknown	SLD70BG	AGLN250	20 Mb/s	unknown	Yes	No	No
DarkLight [10]	Cree CXA 2520	SD5421	Xilinx Artix-7	1.6 kb/s	1.3 m	No	No	No
LiFi-XC	unknown	unknown	unknown	43 Mb/s	unknown	No	Yes	Yes (PureLiFi)
Trulifi 6002	unknown	unknown	unknown	150 Mb/s	2.8 m	No	Yes	Yes (Signify)
Hyperion	186 Lumen power LED	unknown	LimeSDR	unknown	20 m	No	No	Yes (Hyperion Tech)
LiFiMax	unknown	unknown	unknown	100 Mb/s	unknown	No	Yes	Yes (Oledcomm)
LinkRay	Panasonic displays and LED signboards	Mobile phone camera (app required)	unknown	Few kb/s	unknown	No	Yes	Yes (Panasonic)
MetaLiFi-1P	Metachip (MiniLED)	S13954-01CT	unknown	30-230 Mb/s	3 to 25 m	No	Yes	Yes (HCCL Tech)

BeagleBone Black



+

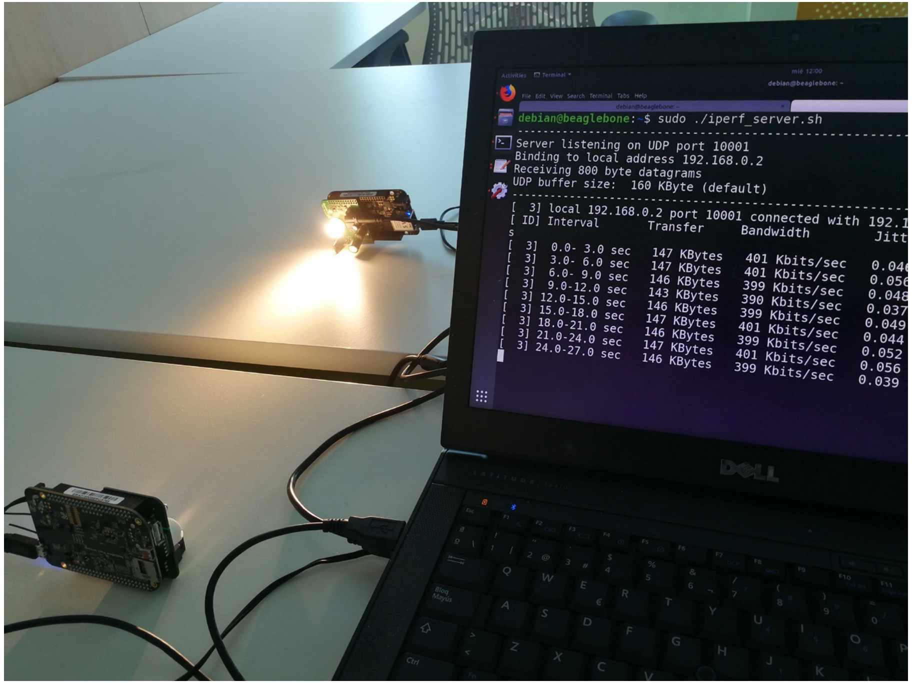
Capes for the different versions of **OpenVLC** (from left to right: pilot, 1.0, 1.1, 1.2, 1.3 and 1.4)



+

B. Genovés Guzmán, M. S. Mir, D. Frómeta Fonseca, A. Galisteo, Q. Wang, D. Giustiniano, “Prototyping Visible Light Communication for the Internet of Things Using OpenVLC”, accepted for publication in IEEE Communications Magazine, 2023.

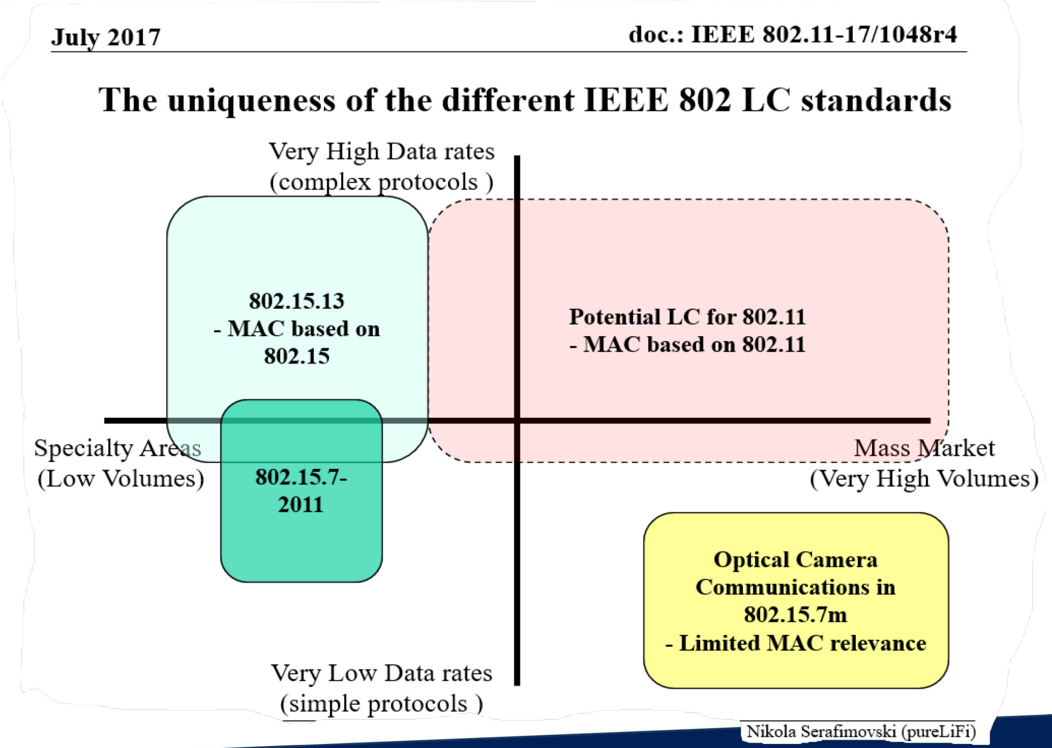
UDP THROUGHPUT WITH OPENVLC



5. STANDARDIZATION AND COMMERCIALIZATION

LIFI STANDARDIZATION EFFORTS

- ITU T Study Group G.vlc: G.9991 and G.9960
- In 2011: IEEE 802.15.7
- In 2021: IEEE 802.15.13
- **In 2023 (recently published): IEEE 802.11bb.**



Q&A

INTERESTING OPEN QUESTIONS FOR IOT

1. How can VLC support multiple IoT devices?

2. How can VLC serve IoT devices with limited energy consumption?

3. How can VLC overcome the shadowing (light blockage)?

4. How can VLC operate during the night?