

# VISIBLE LIGHT COMMUNICATIONS FOR THE IOT

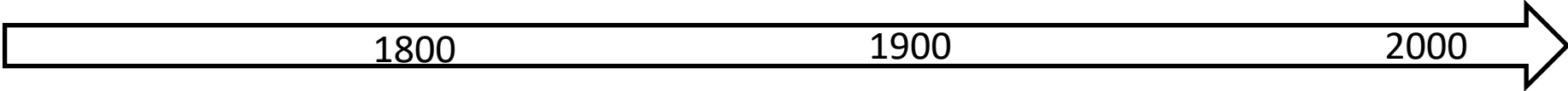
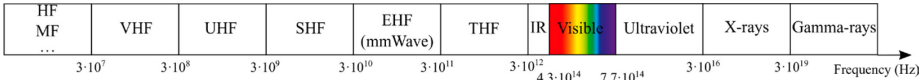
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Borja Genoves Guzman  
Maïté Brandt-Pearce

17th April 2023



# STORYLINE OF VISIBLE LIGHT COMMUNICATION

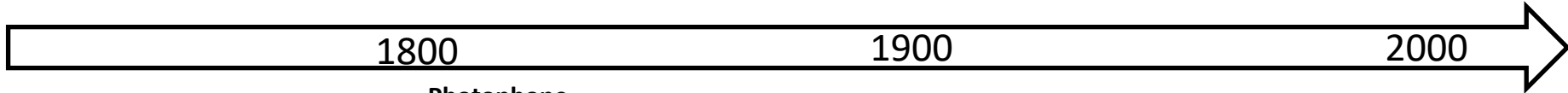
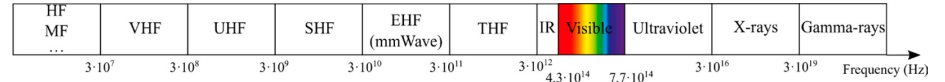


**Smoke signals**  
(900 BCE)



Source: wikipedia

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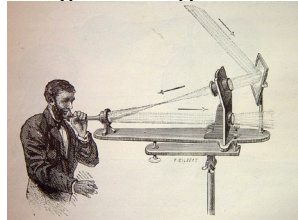
**Smoke signals**  
(900 BC)



Source: wikipedia

**Photophone**

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



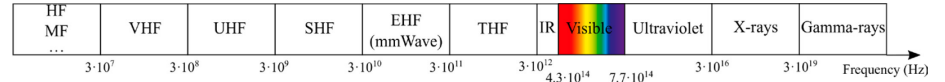
Source: wikipedia

**Incandescent lamp**

Thomas Edison (1880)



# STORYLINE OF VISIBLE LIGHT COMMUNICATION



1800

1900

2000

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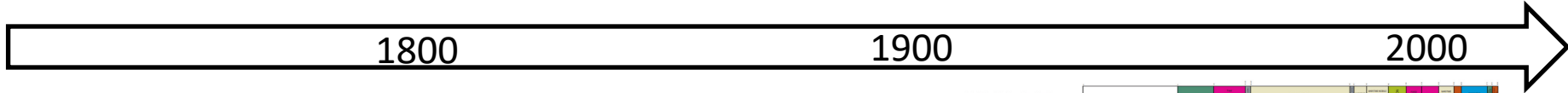
Source: youtube

**Radio, or wireless telegraph**  
Guglielmo Marconi (1890s)



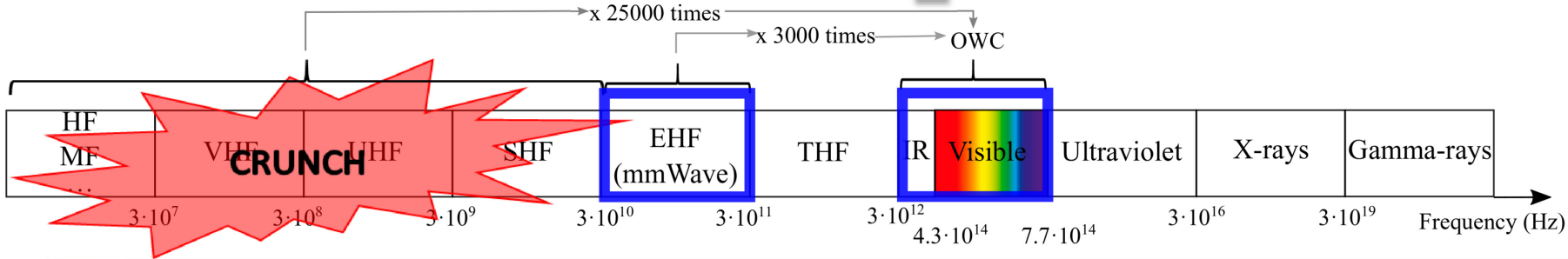
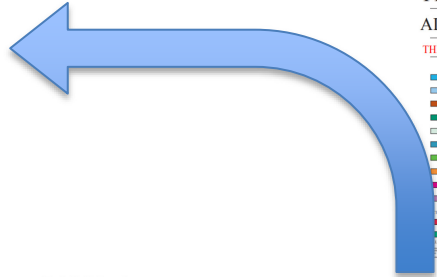
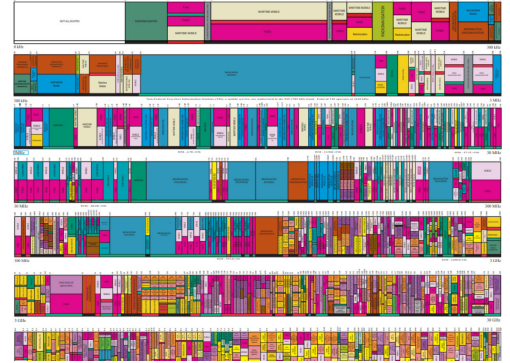
Source: UK Science Museum Group Collection

# RADIO WIRELESS: A VLC STOPPER

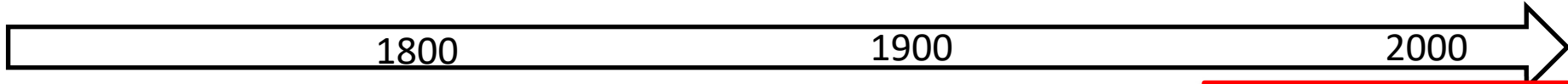
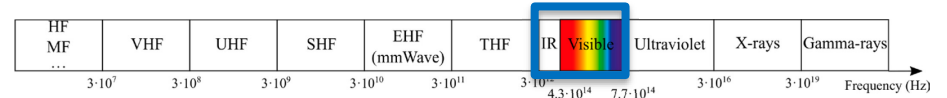


TV remote control

UNITED STATES FREQUENCY ALLOCATIONS THE RADIO SPECTRUM



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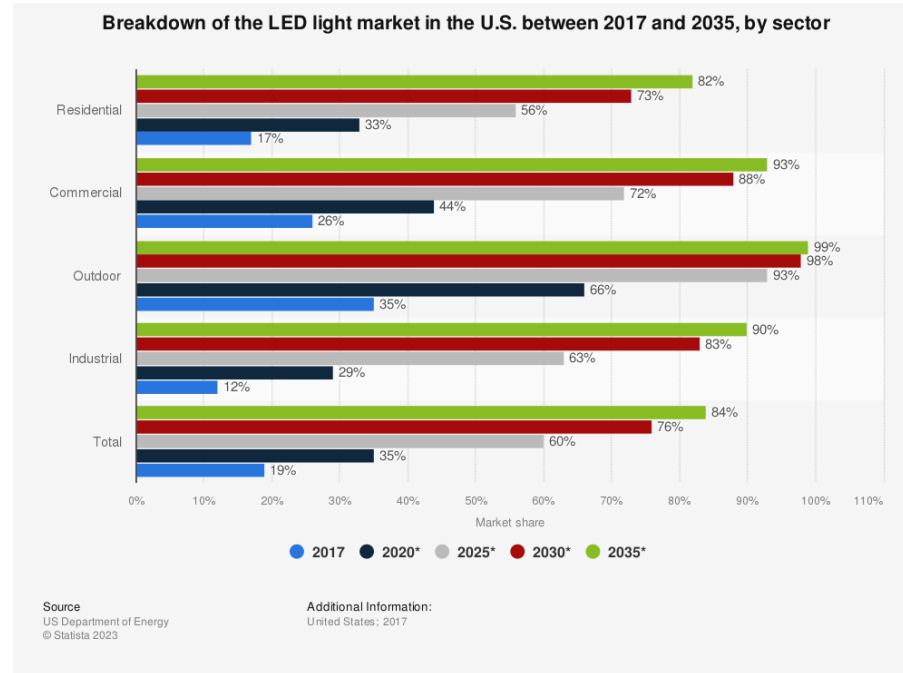
**High-brightness blue LEDs**

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)

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



# 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](http://www.eng.ed.ac.uk)



# LINK BUDGET (EXERCISE)

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

- Communication:

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

- Illumination:

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

Definitions:

$P_{\text{elec,rx}}$  = Electrical received power

$P_{\text{opt}}$  = Optical transmit power

$H$  = Channel gain  $\propto 1/d^2$

$d$  = distance between transmitter and receiver

$n_{\text{PD}}$  = Photodiode responsivity [A/W]

## QUIZ 1

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

- Receiver sensitivity = 0dBm
- Minimum illuminance required (in optical power) = 10dBm
- $K = 20\text{dBm}$

# USE CASES



Industry 4.0



Smart building/ indoor applications



V2x communication

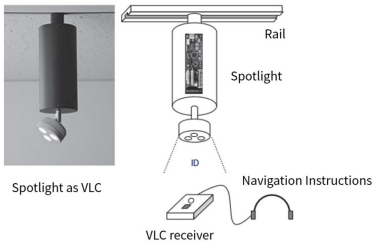


Hospitals

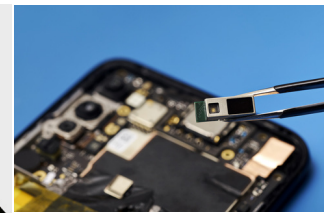
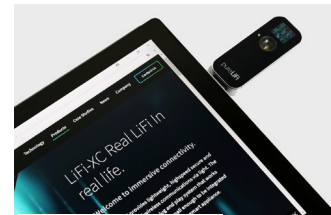


Nuclear power plants

# SUCCESSFUL APPLICATIONS



**TOSHIBA**





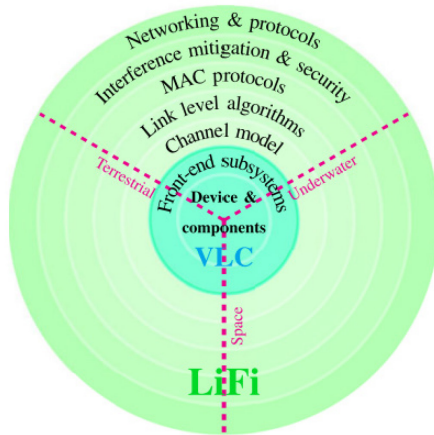
# ***Contents***

1. VLC system overview
2. VLC Hardware
3. PHY layer: VLC Modulation schemes
4. VLC for IoT
  - Key features
  - Prototyping
5. Standardization and commercialization

# 1. VLC SYSTEM OVERVIEW

# LIFI DEFINITION

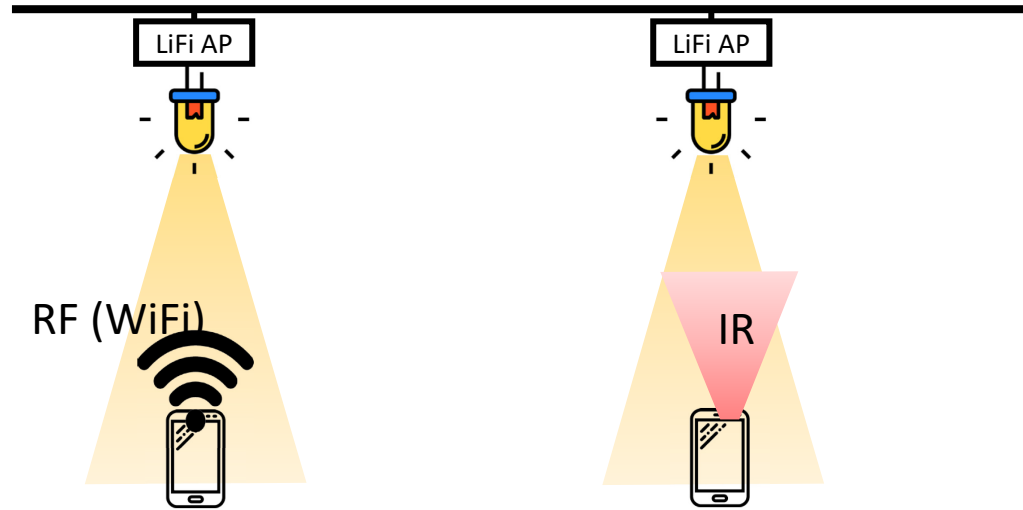
- Point-to-point communication = Visible light communication (VLC)
- VLC in a networked system =



# UPLINK

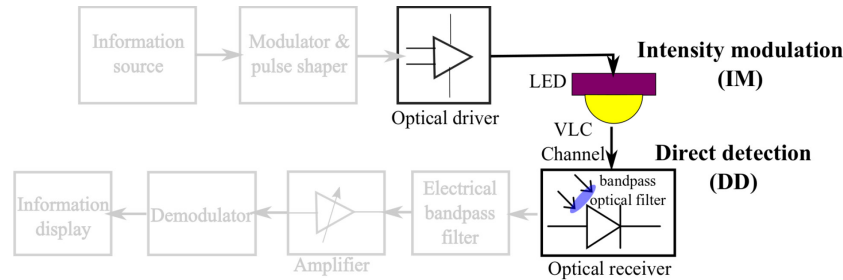
If LiFi is a networked system, it requires an uplink.

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.

## Let's focus on the hardware employed in both the transmitter and the receiver:

- 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

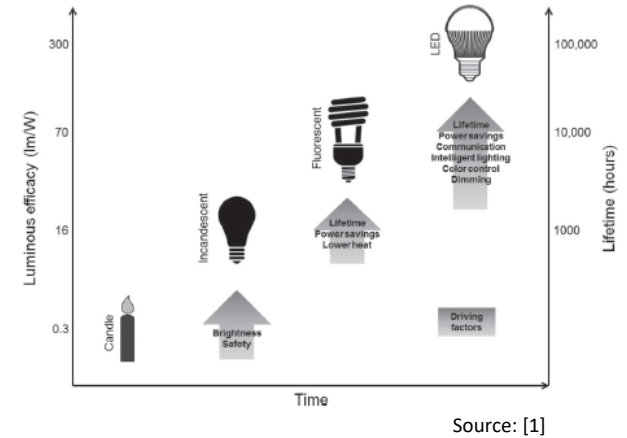
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# TRANSMITTER IN VLC: LED

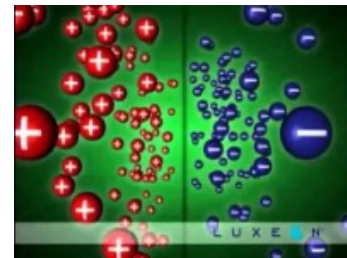
An LED is a solid state semiconductor device which has the capability of changing electrical energy into light energy. [1]

**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.



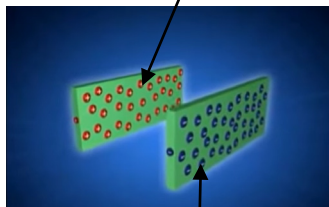
# HOW DOES AN LED WORK?



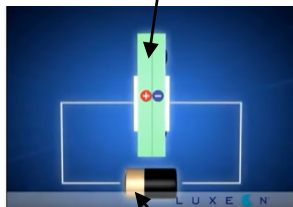
<https://www.youtube.com/watch?v=BH9LI973H8w&t=15s>  
Source: Luxeon

## Electroluminescence

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



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



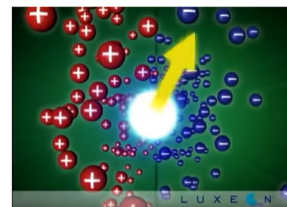
diode

battery

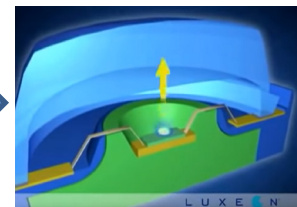
Positive and negative charges  
are forced to move in opposite directions



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

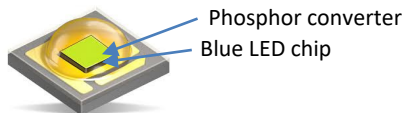


The chip is installed in a package  
that allows an electrical connection



# TYPES OF LED

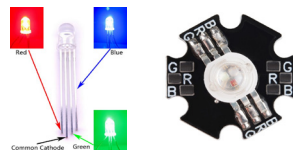
## 1) Phosphor converted LED (pc-LED):



- 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).

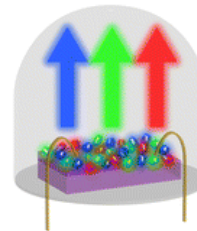
Anyone knows another way of transmitting white light?

## 2) Multi-chip LED (RGB LED):

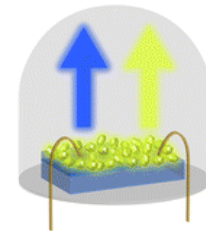


- New modulation schemes: Colour-shift keying (CSK)
- Wavelength division multiplexing (WDM)
- Pros: higher bandwidth.

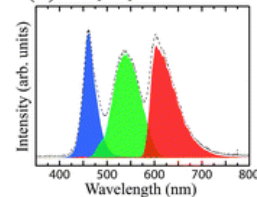
(a) NUV LED + RGB phosphors



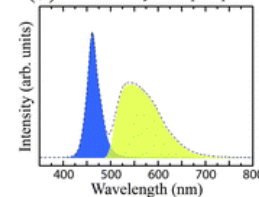
(c) Blue LED + yellow phosphor



(b) RGB phosphors



(d) Blue LED + yellow phosphor



Source: [2]

# TYPES OF LED

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

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

4) Micro LEDs ( $\mu$ LED): AlGaN-based micro-light.

- Large bandwidths ( $\sim 400$  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    |
| InGaAlP - Indium Gallium Aluminum Phosphide | 550-570nm  | Green     |
| SiC - Silicon Carbide                       | 430-505nm  | Blue      |
| GaN - Gallium Nitride                       | 450nm      | White     |

Source: [3]

# 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**  $\eta_{\text{led}}$  as

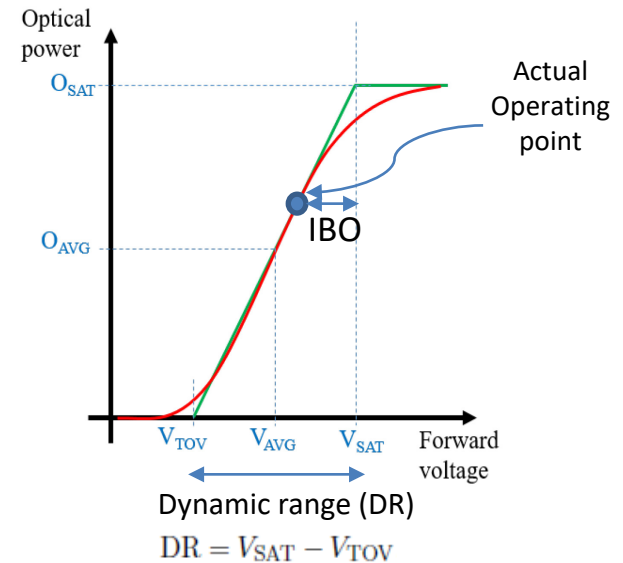
$$P_{\text{opt}} = \eta_{\text{led}} \cdot E\{I(t)\}$$

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

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

The  $\alpha$  and  $B_{\text{DC}}$  values determine the input back-off (IBO)

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



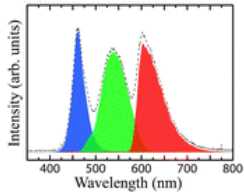
# PROPERTIES OF LED THAT ARE IMPORTANT FOR VLC

- White color for illumination**

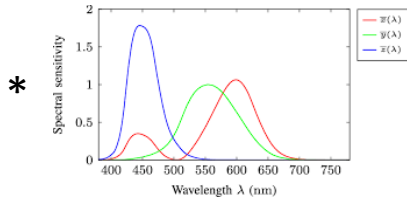
Planckian locus defines the possible Correlated Color Temperature (CCT) points in the CIE 1931 diagram perceived as a white color by humans.

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

## How the CIE 1931 points are computed?

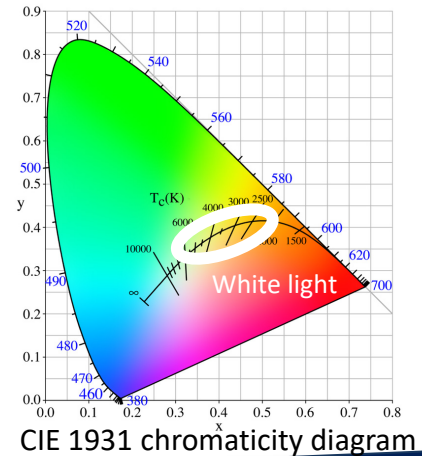


Power spectral density of LED  
 $P(\lambda)$



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

$$\begin{aligned}
 X &= \int_{\lambda} \bar{x}(\lambda) P(\lambda) d\lambda \\
 Y &= \int_{\lambda} \bar{y}(\lambda) P(\lambda) d\lambda \\
 Z &= \int_{\lambda} \bar{z}(\lambda) P(\lambda) d\lambda
 \end{aligned}
 \Rightarrow
 \begin{aligned}
 x &= \frac{X}{X+Y+Z} \\
 y &= \frac{Y}{X+Y+Z}
 \end{aligned}$$



CIE 1931 chromaticity diagram



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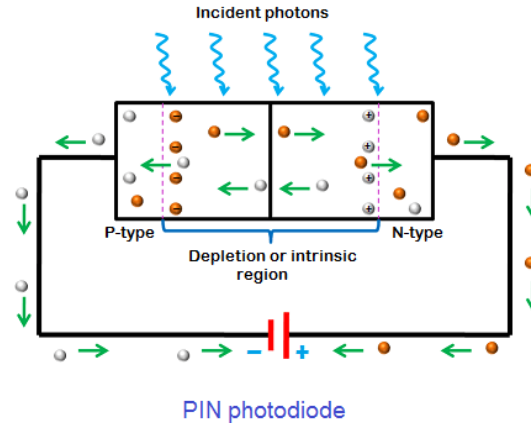
# RECEPTION IN VLC

- 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?

# HOW DOES A PD WORK?

- A PD is a diode operating in reverse bias (since photocurrent generated is in the order of ( $\approx$ ) 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  $\gg$  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  $\rightarrow$  Photocurrent is created

# 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



# TYPES OF RECEIVERS IN VLC

- LED [6]:
  - They have photo-sensing characteristics.
  - Detects reduced wavelength range → 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 → 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

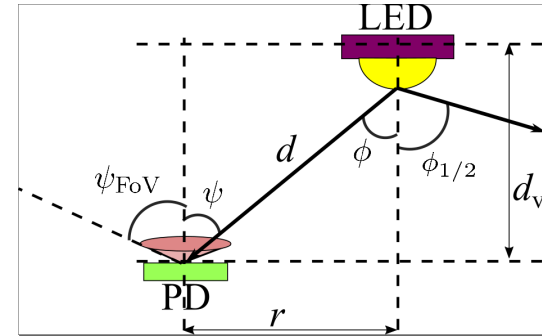
Photocurrent generated by the PD is proportional to the received optical power

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

where  $\eta_{\text{pd}}$  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.



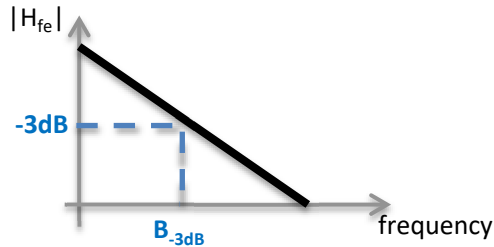
# HOW DO THE FRONT-END DEVICES AFFECT TO THE END-TO-END CHANNEL?

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

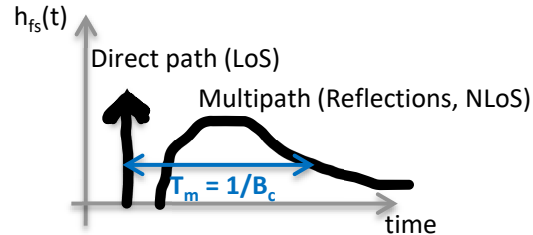
Optical wireless communication channel:

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

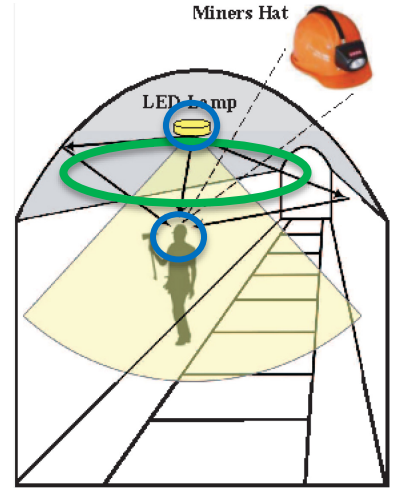
Front-end elements channel



Free-space channel



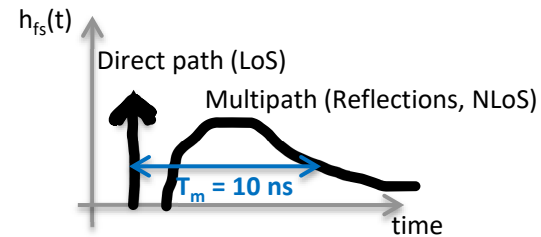
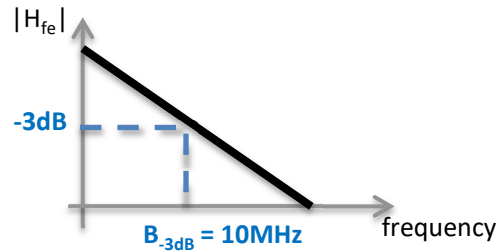
$B_c$  = coherence bandwidth, i.e., range of frequencies where the bandwidth is considered flat



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

# 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)

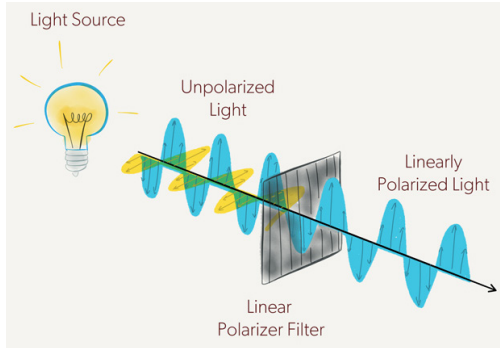
- Shot noise: Produced by the fluctuation in number of photons that arrive to the destination.
- Thermal noise: Produced by the thermal agitation of electrons in the resistive units at the receiver.
- Clipping noise: Produced by sending samples out of the LED's dynamic range (be careful with PAPR in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

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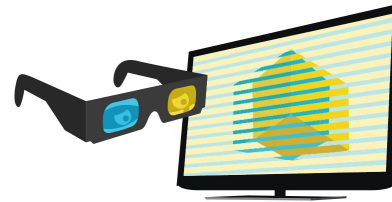
# ADDITIONAL MATERIALS FOR VLC

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



Source: photopills.com

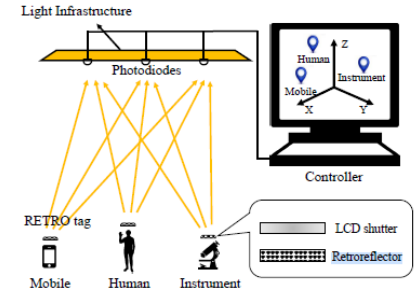
## Polarized 3D system (cinema)



# ADDITIONAL MATERIALS FOR VLC

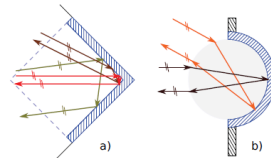
- Retroreflector:

- 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]

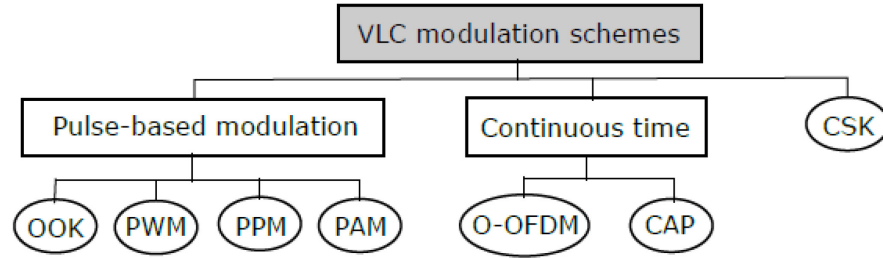
- Applications: Positioning systems (RSSI + trilateration), backward channel with low data rate (IoT), passive communications, etc.
- **Passive VLC:** transmitter (**mirrors or LC shutter**) allows much energy savings:
  - **Passive** consumes **hundreds of uW** vs. **active** transmissions (WiFi, ZigBee,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

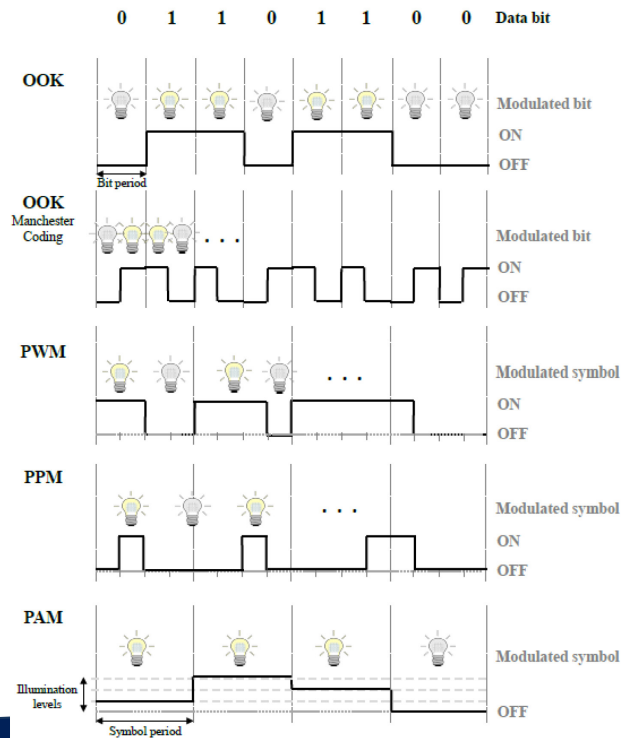
# MAIN MODULATION SCHEMES IN VLC



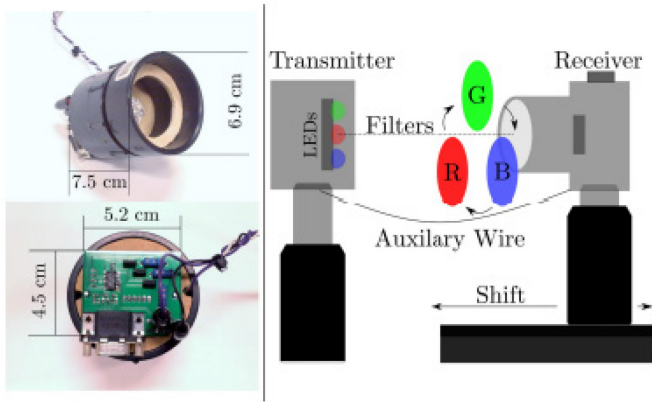
- On-Off-Keying (OOK)
- Pulse-Width Modulation (PWM)
- Pulse Position Modulation (PPM)
- Pulse Amplitude Modulation (PAM)
  
- Optical Orthogonal Frequency Division Multiplexing (O-OFDM)
- Carrier-less Amplitude and Phase modulation (CAP)
  
- Color Shift Keying (CSK)

# PULSE-BASED MODULATION SCHEMES

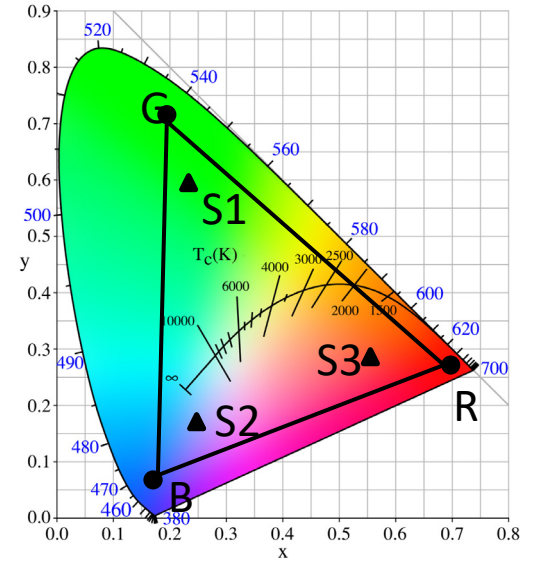
- On-Off-Keying (OOK)
- Pulse-Width Modulation (PWM)
- Pulse Position Modulation (PPM)
- Pulse Amplitude Modulation (PAM)



# 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

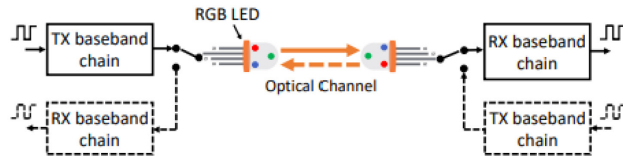


# 4. VLC FOR IOT

# KEY FEATURES FOR IOT

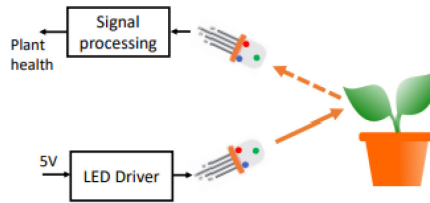
- Light Emitting Diodes (LEDs) are driving a revolution in lighting systems.
- Entering the Internet of Things (IoT) market with **embedded sensory functionalities**.
- Visible Light Communication (VLC) → LED revolution with the language of **ubiquitous networks**.
- IoT systems can leverage the **low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

## Multifunctionality of RGB LEDs for IoT:



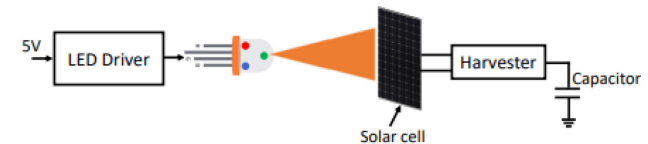
(a) RGB LED bulb as VLC transmitter and receiver.

### a) Communication



(b) RGB LED bulb to sense environmental parameters.

### b) Sensing



(c) RGB LED bulb to optimize energy harvesting.

### c) Energy harvesting.

# PROTOTYPING VLC FOR IOT

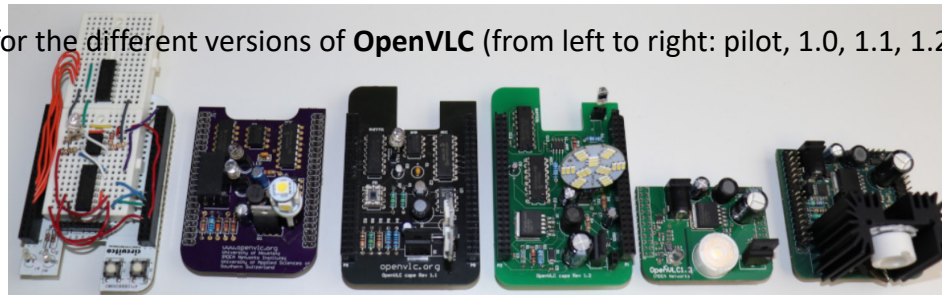
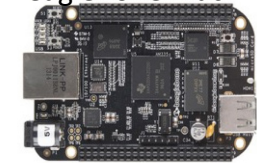
A summary of state-of-the-art VLC platforms and implementations:

| 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-430DD                       | SFH205P                            | 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)     |

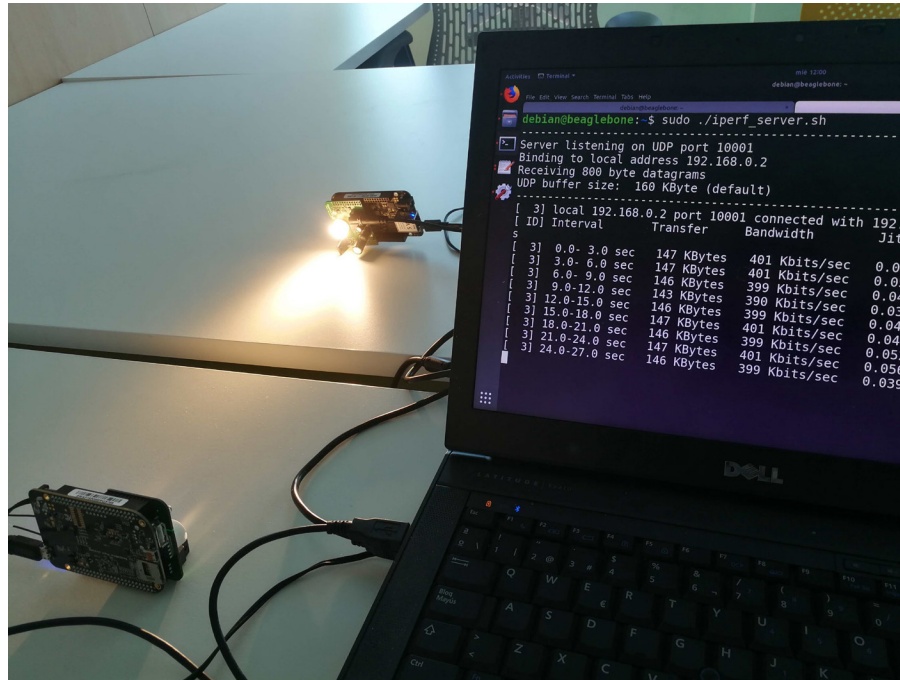
**OPENVLC**  
<http://www.openvnc.org/>

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)



# UDP THROUGHPUT WITH OPENVLC



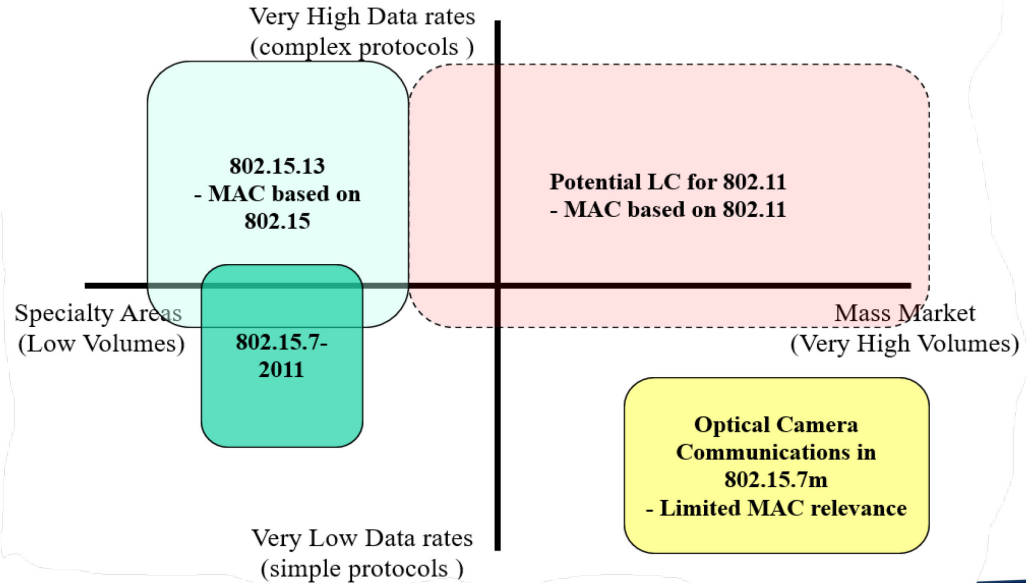
# 5. STANDARDIZATION AND COMMERCIALIZATION

# LIFI STANDARDIZATION EFFORTS

July 2017

doc.: IEEE 802.11-17/1048r4

## The uniqueness of the different IEEE 802 LC standards



Nikola Serafimovski (pureLiFi)

- 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?