Visible Light Communications

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University of Rome "La Sapienza"

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Slides partly by Domenico Giustiniano *et al.*

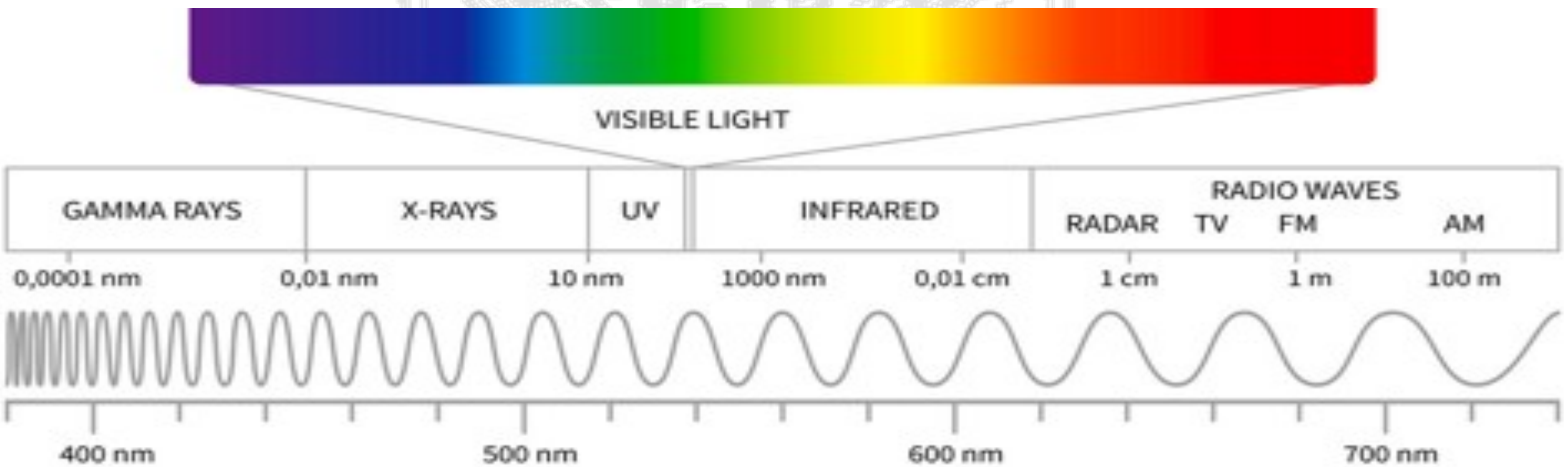
Why Visible Light Communication?

- Just an example: video streaming…
- Distribution of online content through the web is expected to dominate video entertainment.
- High definition video, telepresence applications pose stringent requirements on access networks
  - Almost half of traffic volume on the Internet!
- DSL support an aggregate downstream and upstream data rate of 1Gbps at distances < 100m.
- FTTC and FTTH is considered as a technology for the realization of broadband access networks.

How to distribute traffic inside home or office???

Options for high speed distribution

- Wireline: who uses cables anymore?
- Wireless (radio frequency): close to saturation!
- Optical solutions
  - infra-red (Ir)
  - visible light communication (VLC)



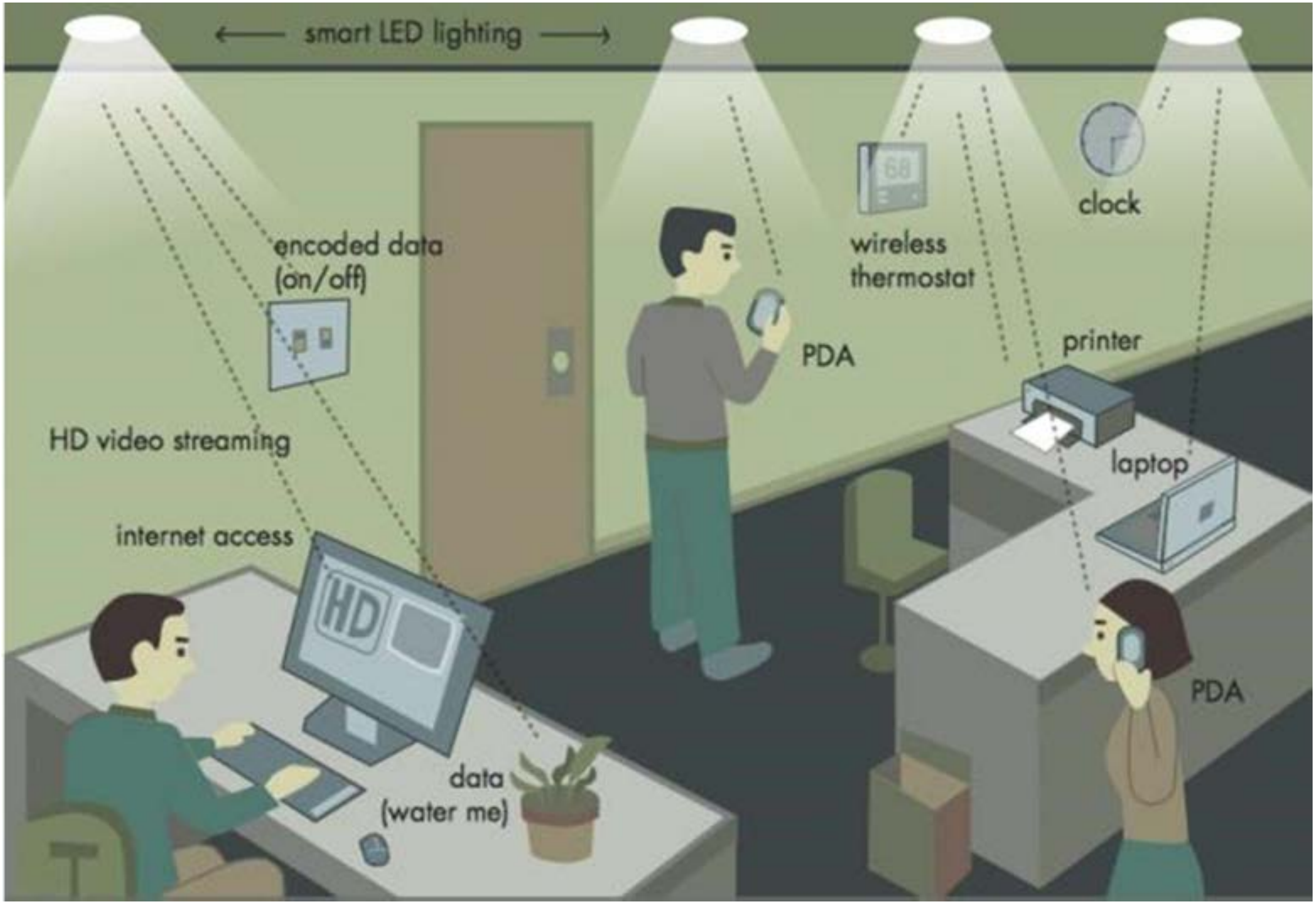
Potential of VLC

- Visible light spectrum is 10,000 times larger than RF
  - Radio communication spectrum up to 70 GHz
  - Visible light goes from 400 THz to 790 THz
- Visible light spectrum is freely available (no licensing)
- Light doesn't penetrate through walls
  - Spatial reuse opportunities thanks to spatial confinement
  - Inherent security
- The human eye tolerates a high dynamic light changes
- Relative immunity to multipath fading
- Predictable direction of communication (Field of View)
- Not limited to line-of-sight (diffused light)
- No EM interference

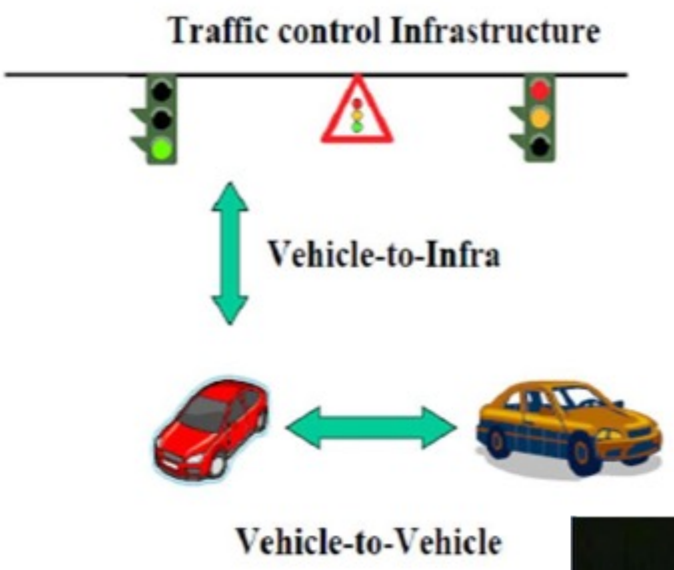
VLC vs Ir

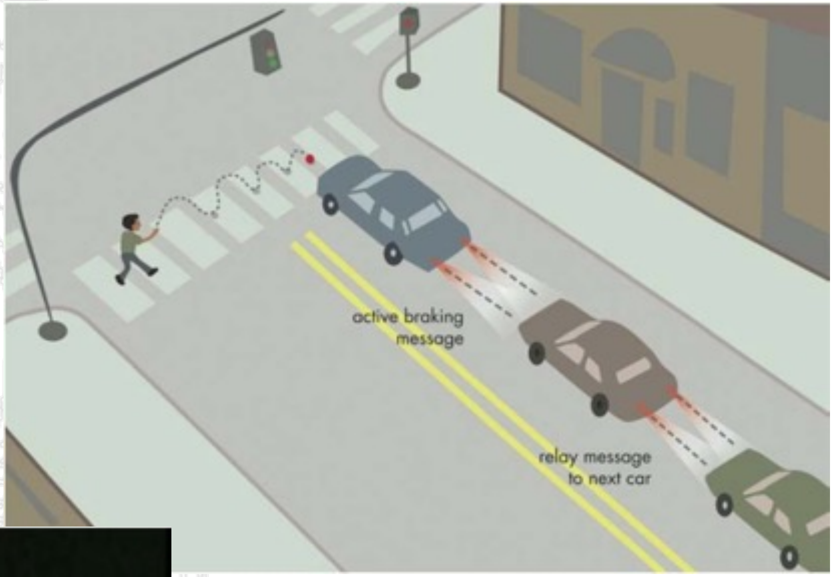
- Similar frequency ranges
- Safety problems using IR for transmission at high power
- InfraRed Data Association (IrDA) protocol stacks for point-to-point links in Personal Area Networks
  - By modifying the IrDA specification, existing IrDA optical modules can be used for VLC data-transmission.
- Giga-IR standard uses lasers, rather than LEDs
  - expensive transceivers, hazardous for human eyes…
- LEDs are used for ambient illumination, infra-red not.

Office use-cases



Outdoor traffic scenario





RF sensitive areas

- Airplane, nuclear plant, …

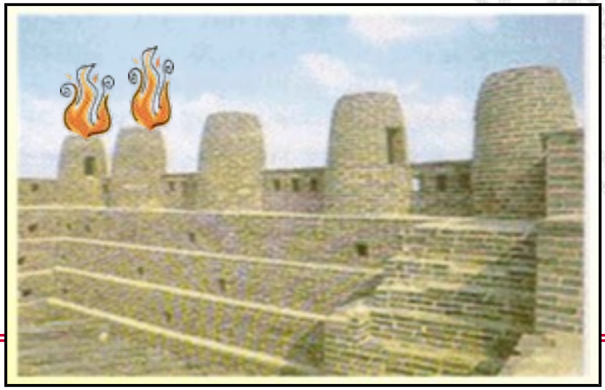
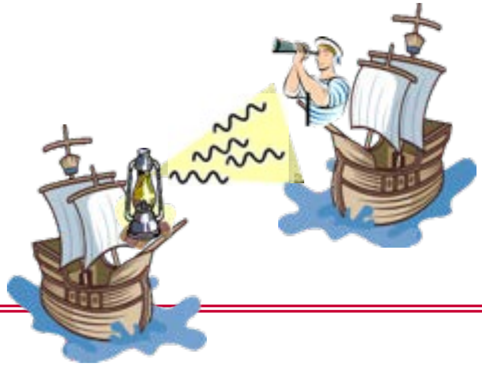
Any closed environement!

- Wherever lighting is already there
- Hospital, museum, …

Is it new?

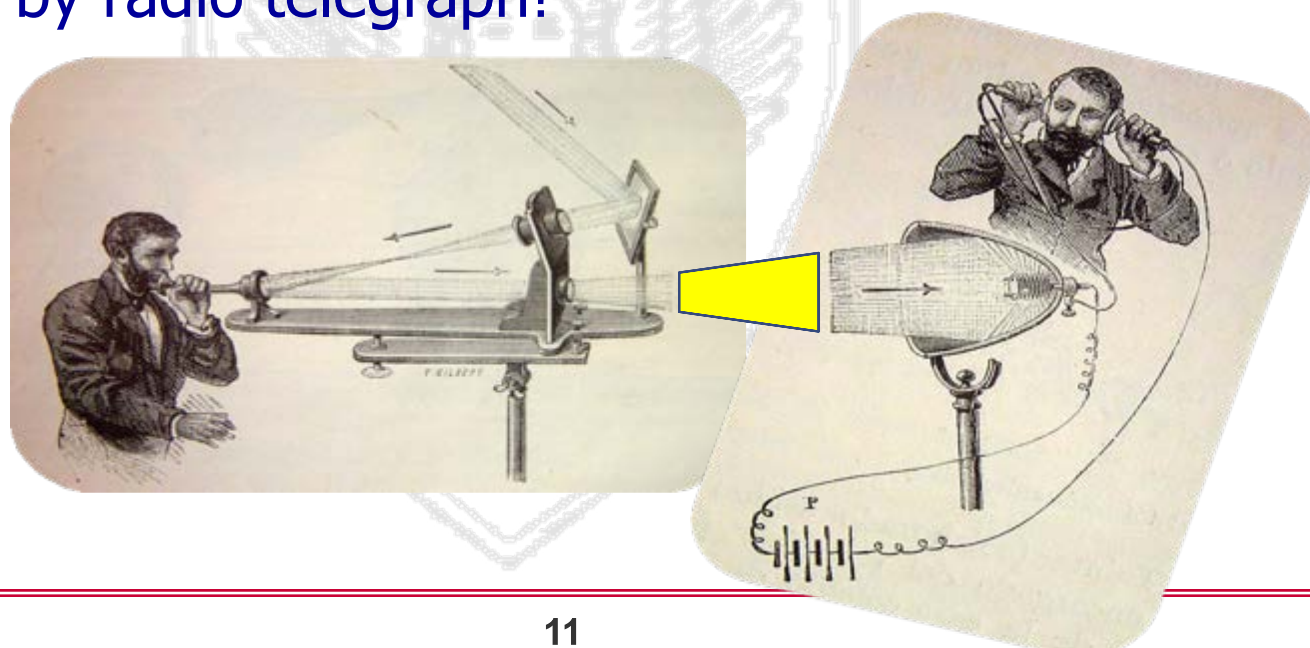
- Information delivery through reflection by mirror (Heliograph)
- The use of fire or lamp
  - Beacon fire, lighthouse, ship-to-ship comm. by Morse code…



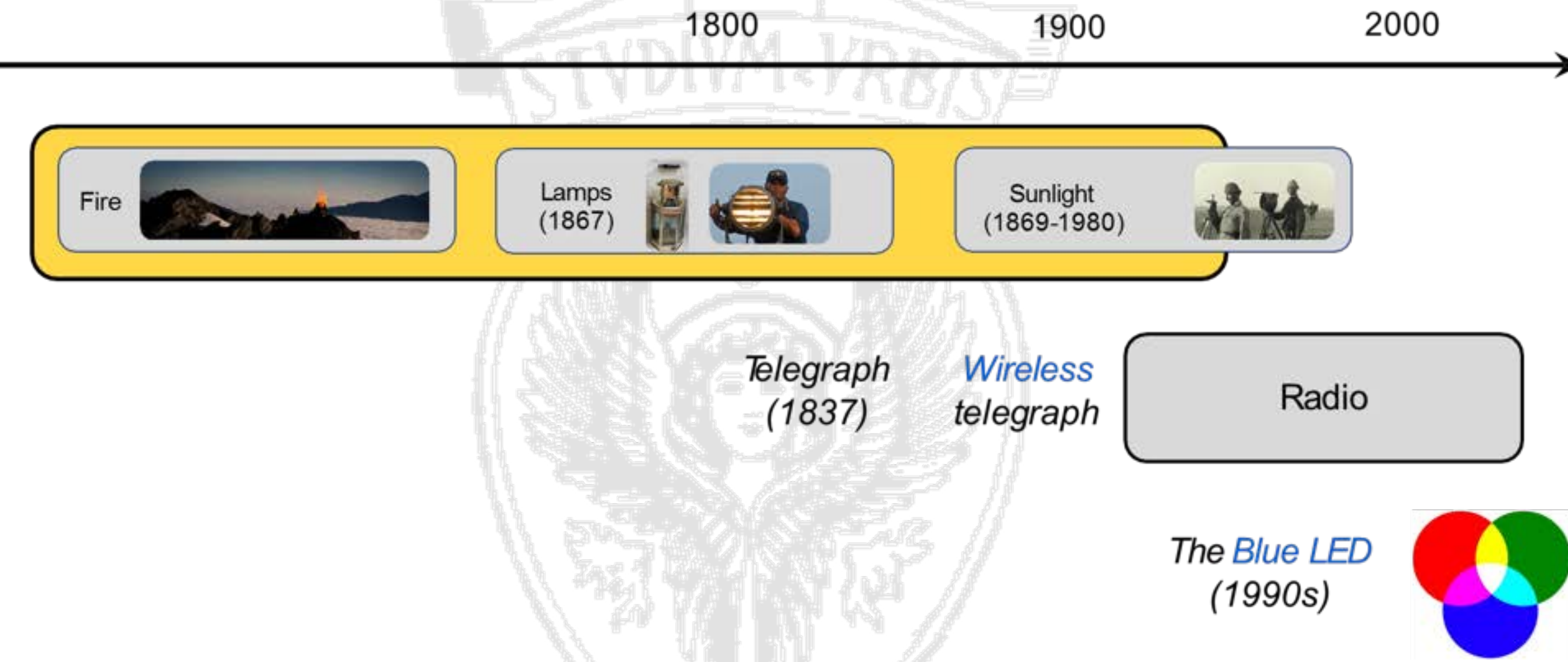




Why did it stop?

- In 1880, Alexander Graham Bell invented the photophone
- Optical source: sunlight
  - Externally modulation by vibrating mirror
- Receiver: parabolic mirror with crystalline selenium cells
- Killed by radio telegraph!



Why did it resume?



The Blue LED, Nobel Prize in Physics 2014

"Scientists developed LEDs that emitted everything from infrared to green light… but they couldn't quite get to blue"

LED basics

Lighting systems

- Incandescent bulb
  - First industrial light source
  - 5% light, 95% heat
  - Few thousand hours of life

- Fluorescent lamp
  - White light
  - 25% light
  - 10,000s hours

- Solid-state light emitting diode (LED)
  - Compact
  - 50% light
  - More than 50,000 hours lifespan

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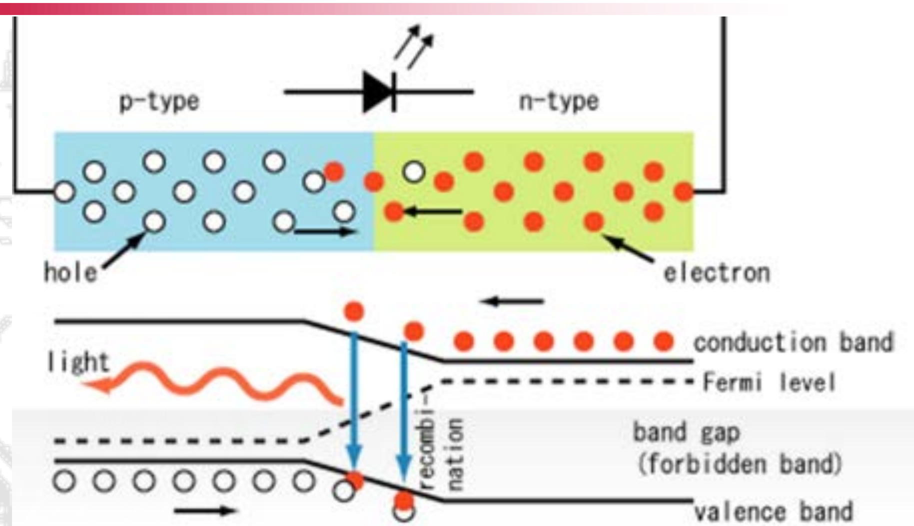
How does an LED work?

- Light Emitting Diode (LED)
  - Two semiconductors with opposite p/n "doping" attached together



p-type semiconductor (positively charged carriers = holes)

diode

battery

n-type semiconductor (negatively charged = electrons)

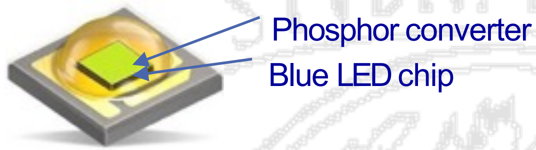
Positive and negative charges are forced to move in opposite directions

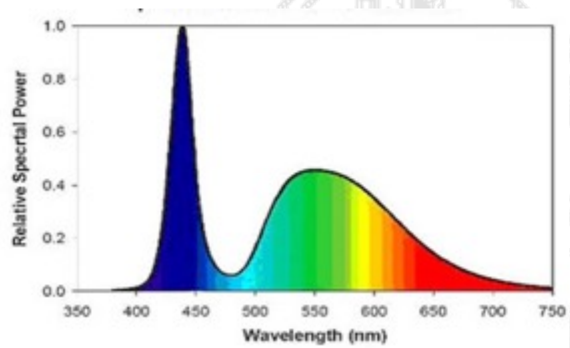
The chip is installed in a package that allows an electrical connection

Hole is at a lower energy level than electron. Electron must release energy to combine with holes = photons

Types of LEDs

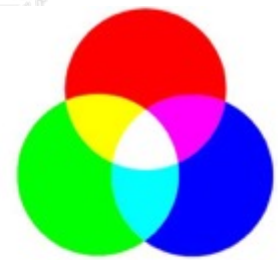
Blue chip + Phosphor

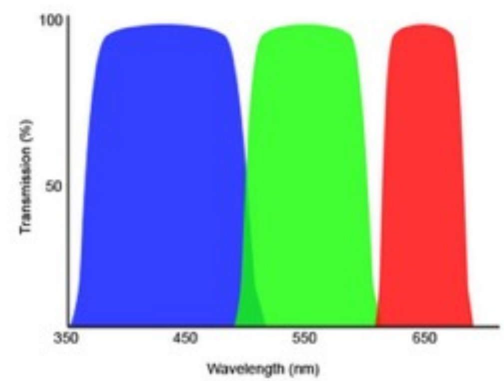




Blue LED chip + phosphor coating. Depending on the amount of phosphor: warm-, neutral, cool-white.
Pros: low complexity, price and good Color Rendering Index (CRI). Popular for today general lighting

RGB



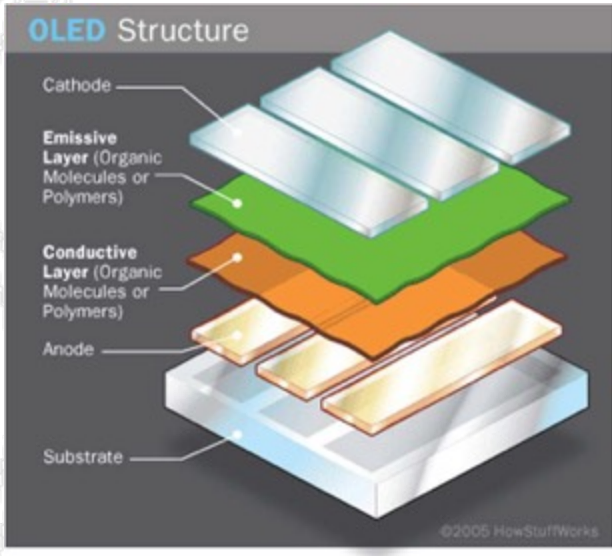


New modulation schemes: Colour-shift keying (CSK), Wavelength division multiplexing (WDM), OFDM
Pros: higher bandwidth.

Other LEDs

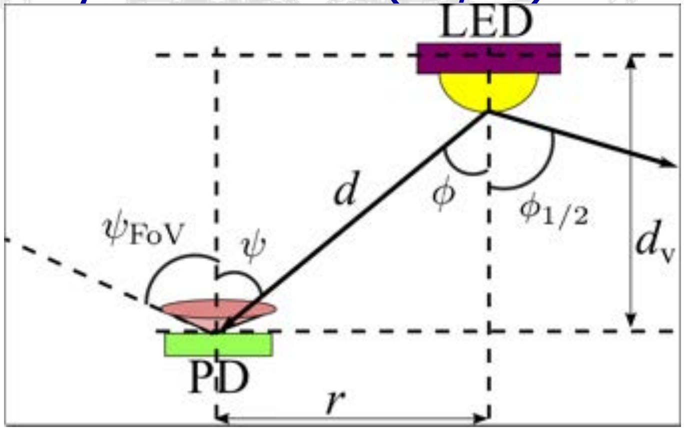
- Organic light emitting diode (OLED): use of an organic layer between positive and negative carriers.
  - Lower bandwidth than inorganic LEDs.
  - Lower lifetime than inorganic LEDs.
- Micro LEDs: AlGaN-based micro-light.
  - Large bandwidths (~400 MHz) due to low capacitance in LEDs.
- Both are typically used for flat panel displays.

OLED



Properties of LEDs

- Don’t forget that VLC must also comply with illumination requirements if it is installed in a realistic room:
  - Average illuminance
  - Illuminance uniformity
- The power transmission of an LED varies with the direction (more later)
  - Luminous flux of the LED (lumens, lm)
  - Luminous efficacy of the LED (lm/W)



Properties of LEDs for VLC

- Power transmission of an LED varies with the direction
  - Optical transmit intensity at an angle ϕ (Lambertian law)

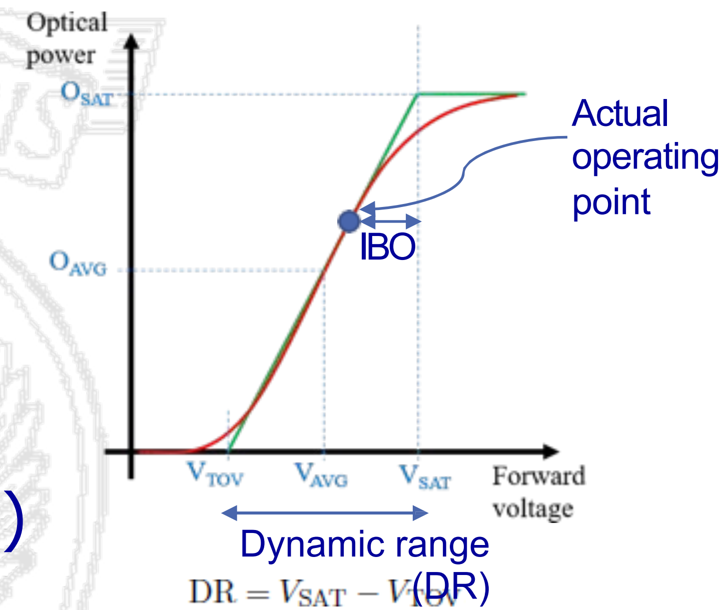
$$P_{\mathrm{opt}} R(\phi) = P_{\mathrm{opt}} \frac{m+1}{2\pi} \cos^m(\phi) \quad [\mathrm{W/sr}]$$

- where
- P_{opt}: is the optical transmit power
- $R(\phi)$: radiation profile of the LED dependent on the transmission direction angle ϕ
- m: Lambertian emission order computed with the half-power semi-angle $\phi_{1/2}$ which can be modified by using proper optical elements

$$m = -\frac{1}{\log_2\left(\cos(\phi_{1/2})\right)}$$

Non-linear transfer function

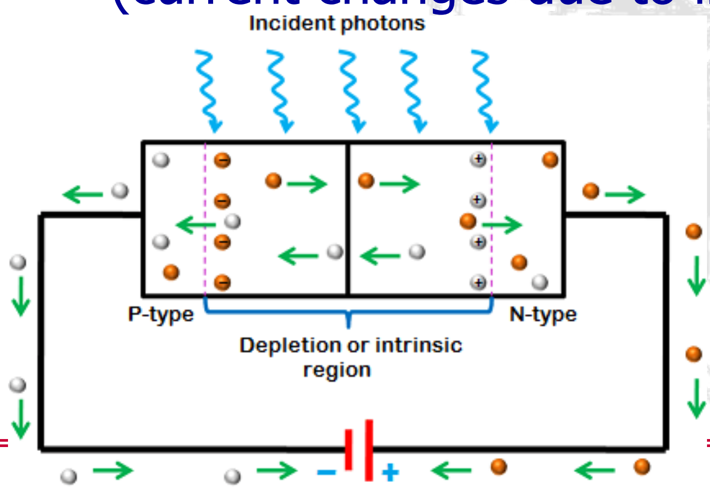
- The input real signal must be scaled and biased to work within the Dynamic Range (DR)
- Be careful with peak-to-average power ratio (PAPR) of input signals.
- Must consider input back-off (IBO)
- Finally, the output optical power P_{opt} is linear with the forward current I(t) times the efficiency of the LED η_{led}
  - $P_{opt} = \eta_{led} \cdot E\{I(t)\}$



Light Detectors

Reception in VLC

- Receiver captures light and converts it into electrical signal
- Typically a photodiode (PD) is used in VLC, but some other receivers may also be used, e.g. cameras or LEDs
- A PD is a diode operating in reverse bias: photocurrent generated is in the order of diode current range and can be detected in the change of current due to illumination.
  - Differently, in forward bias, Diode current >> photocurrent (current changes due to illumination can not be detected).



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

Types of PDs

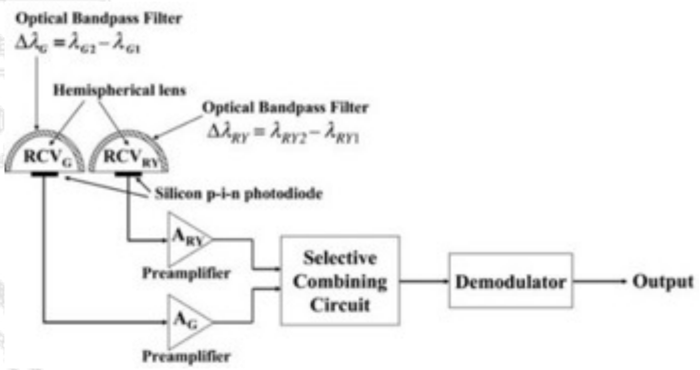
- PIN PD
  - p-type semiconductor + undoped intrinsic semiconductor + n-type semiconductor
  - Responsivity in the range of 0.2 and 0.4 A/W.
  - Achievable 3-dB bandwidth is hundreds of MHz and even GHz
  - Suitable for environments with relatively high intensity light
- Avalanche PD (APD)
  - High current gain due to impact ionization when applying a high reverse bias voltage.
  - Responsivity typically higher than unity.
  - Extra noise and sensitive to temperature changes.
  - Suitable for weak incident light intensity

Other light detectors

- LED
  - 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)
  - Image sensors can spatially separate light sources
  - Multiplexing techniques not required
- Solar panels
  - Communication + energy harvesting possible

Receiver configuration in VLC

- Single element receiver
  - Traditional configuration: 1 RX.
- Selective combining receiver:
  - Multiple RXs and select the one with better performance
- Image diversity receiver:
  - Multiple transmitters + array of PDs
  - Imaging lens:
    - ✓ Focuses the beams onto the PDs
    - ✓ Acts as an optical collector
- Receiver configuration must be chosen depending on the system needs and application



Selective combining receiver

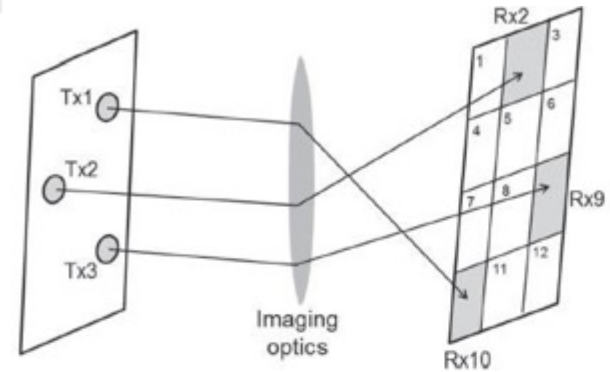
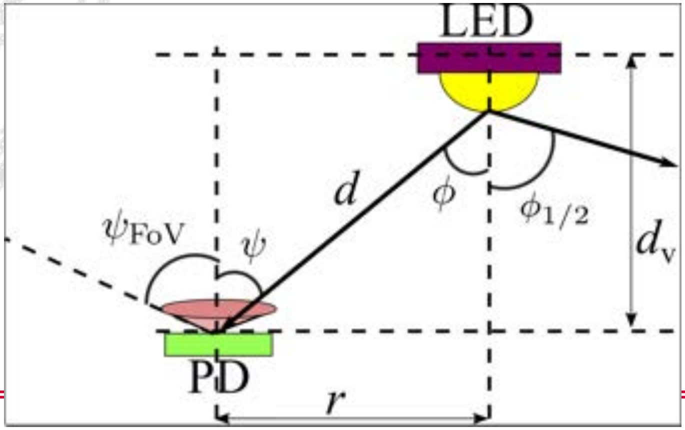


Image diversity receiver

Properties of PD 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 (increased receiver gain) $g_c = G_c 1(\psi) = \frac{n_{\text{ref}}^2}{\sin^2(\psi_{\text{FoV}})} 1(\psi)$
  - where n_{ref} if the refractive index of the material
  - Filter to eliminate signals out of the desired band (typically extra loss due to absorption and reflection)



Pre-amplifiers

- A pre-amplifier at the receiver is required to amplify the weak current at the PD output.
  - Low impedance amplifier
  - High impedance amplifier
- Trade-off between rate and sensitivity
  - If impedance amplifier is high, then Thermal noise low and sensitivity high. But BW is low (an equalizer could be employed)
  - If impedance amplifier is low, then thermal noise is high (predominant) and system becomes impractical
- Trans-impedance amplifier
  - Converts the input current to a proportional output voltage.
  - The most used due to balance between sensitivity and BW.

Modulation and communication challenges

Modulation Techniques for VLC

- Direct Modulation
  - The data/information is used to directly modulate the electrical current driving the light source.
- Simple and cheap to implement.
- Can be used for both coherent and non-coherent optical sources. Modulates only the light intensity (intensity modulation).
- Direct detection (DD) at the receiver with photodetector.
- For low speed applications, up to a few Gbps. Primarily due to limitation of electronic driver circuitry.
- Indirect Modulation offers higher data rates
  - For coherent light sources and coherent detection
  - Relatively more complex and more expensive (not for VLC)

Modulation basics

- It is not possible to modulate phase and amplitude
  - LEDs produce incoherent light
  - light waves not in phase with each other
- Intensity modulation
  - Intensity can be modulated very quickly (order of MHz)
  - Much faster than conventional lighting
  - Encode info in number of photons being emitted
  - Modulate waveform into instantaneous power
- Direct detection with photodetector
  - Get current proportional to received instantaneous power

Modulation basics (2)

- You cannot have negative number of photons
  - Positive, real-valued signals only
  - Real-valued RF modulation schemes can be used, other modulations have to be adapted
    - ✓ On-off keying (OOK)
    - ✓ Frequency-shift keying (FSK), Color-shift keying (CSK),
    - ✓ Pulse amplitude modulation (PAM), Pulse width modulation (PWM)
    - ✓ Orthogonal Frequency Division Multiplexing (OFDM)
- Complex-valued baseband signals must be pre-converted
  - I and Q signals transformed into real and positive values
- Past a certain rate, Inter-Symbol Interference ruins perfomance
- Lots of work devoted to advanced PHY schemes for VLC

Recent examples

- High-data rates achieved through sophisticated PHY schemes
- Strive to offer an alternative to Wi-Fi (Li-Fi)

	Range (m)	Data rate	Modulation	Year
Langer *et.al.*	1.5	230Mb/s	OOK	2010
Khalid *et.al.*	0.5	1Gb/s	OFDM	2012
Kottke *et.al.*	0.3	1.25Gb/s	OFDM	2012
Sewaiwar *et.al.*	0.85	3Gb/s	OFDM+RGB	2015

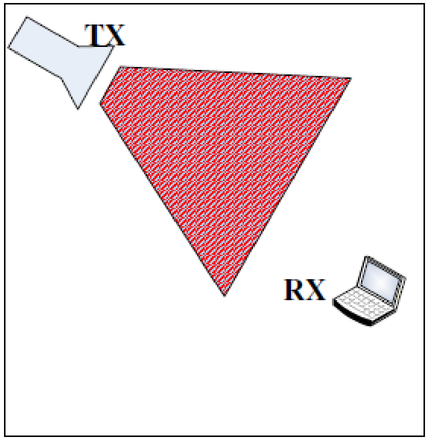
- More recently, VLC available for networked embedded systems
  - Focus on low-end IoT devices -> Internet of Light!
  - Low speed, reasonable range

Specific communication issues

- **Communication during day time (light is off)!**
  - When the lights should be OFF, power required for VLC is not free
- **Flickering**
  - Modulation occurs at relative high speeds
  - filtered out by the human eye (= lowpass filter)
  - However flicker may occur between frames, modulating at low rate
- **Interference by sunlight!**
  - Photodiode saturation in direct sunlight
  - But most of noise can be filtered out (passband filter)
- Link dynamics?
- Bidirectional links?
- Dense LED Illumination deployments?

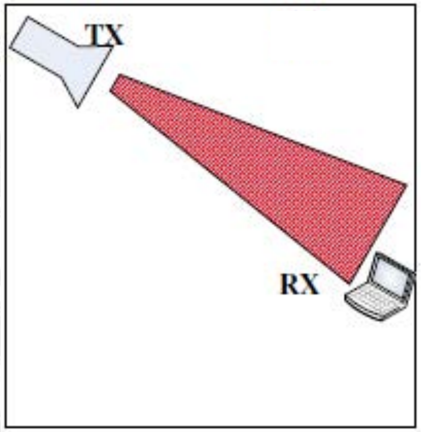
Optical wireless links

- Several communication models



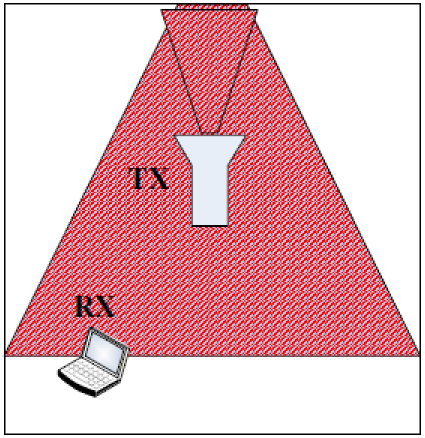
- Line of sight (LOS):

  Transmitter beam is wide enough to cover a relatively large portion of the room. Better coverage area, but higher optical losses.



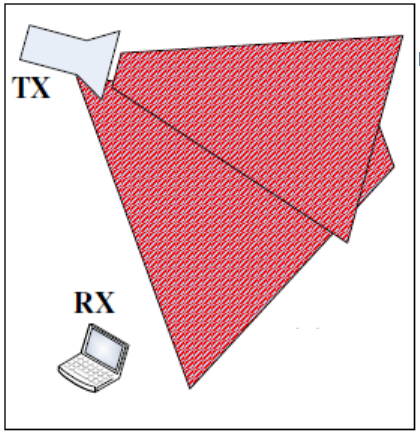
- Narrow LOS:

  Transmitter beam is narrow and covers only a small portion of the room. Limited geometric losses and coverage.



- Quasi diffuse:

  Transmitter points towards the ceiling and terminals illuminated through reflection of the beam. Optical losses more pronounced.

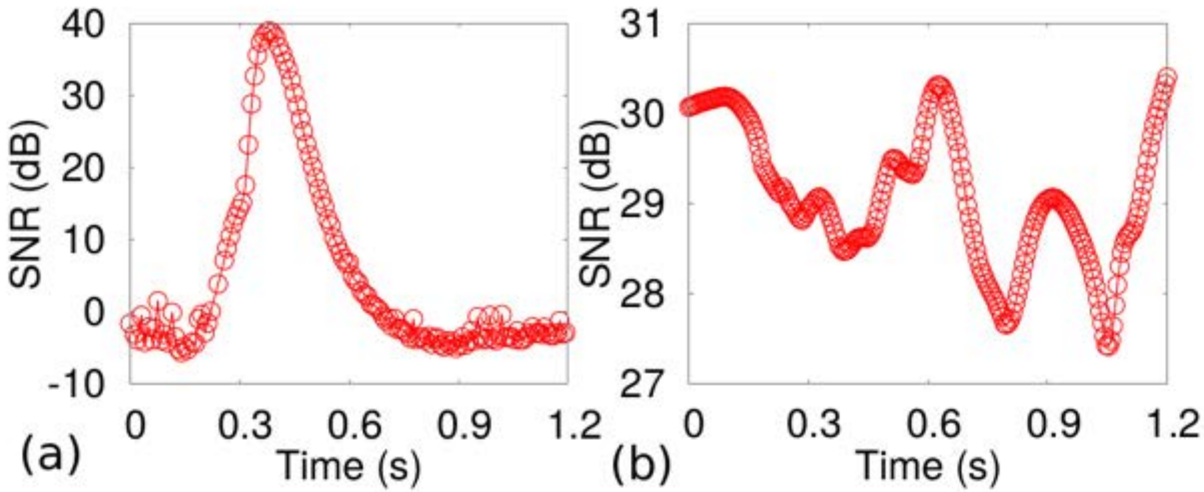


- Diffuse:

  No direct LOS path. Communication achieved through beam reflections at the surfaces of the room.

Link dynamics

- Maintaining VLC performance under link dynamics is a challenging problem

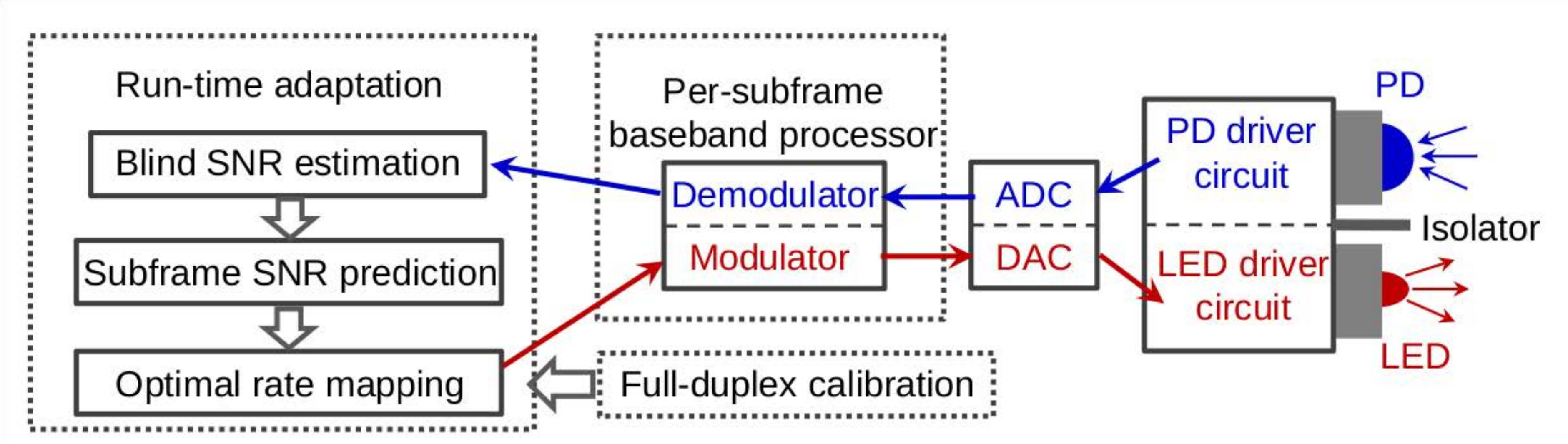


SNR variation in walking in-and-out scenario:(a) VLC (b) WiFi

- Highly dynamic spatial/temporal variations can not be tackled by conventional rate adaptation protocols
  - A packet may last several hundred milliseconds!

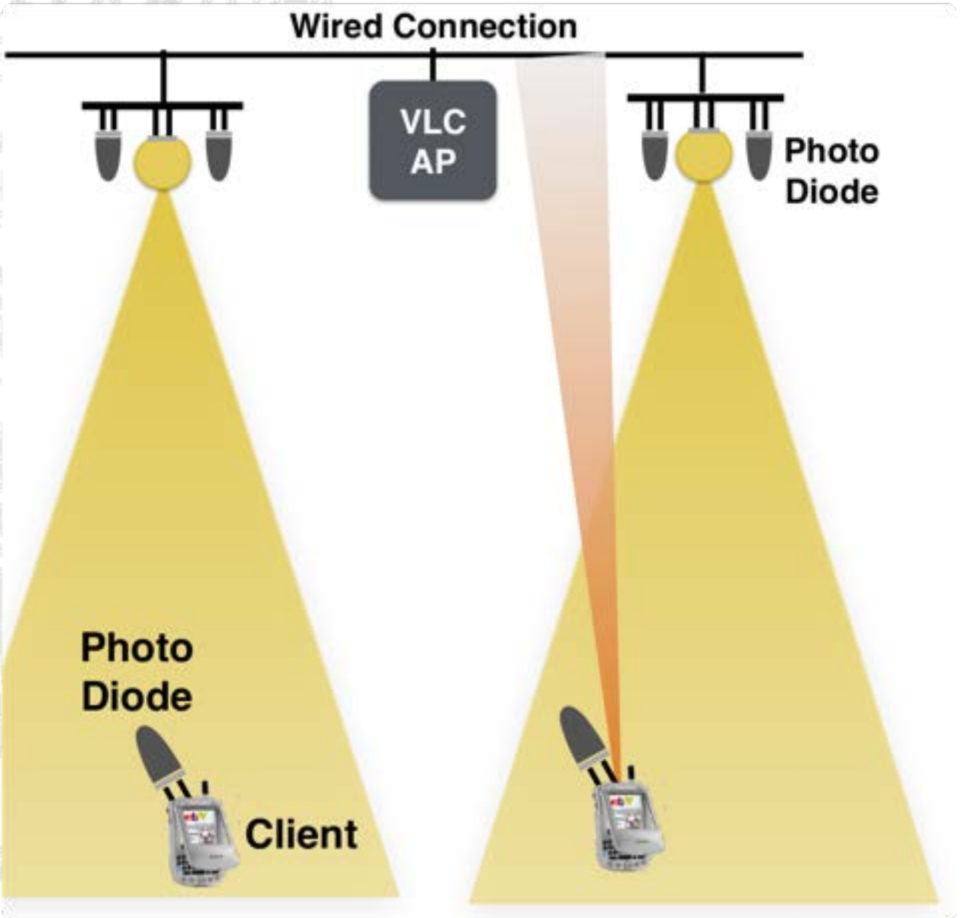
SNR Prediction

- Possible solution thanks to channel predictability
  - SNR values varies quickly
  - But highly stable first and second-order statistics of the link SNR
- Full-duplex to collect statistics
  - Send SNR measurements to transmitter
- Map SNR to PHY rate for a fixed subframe size



VLC + WiFi?

- Narrow field-of-view and Rotational misalignment can affect uplink
- Possible solution: RF-based uplink
- Wider coverage

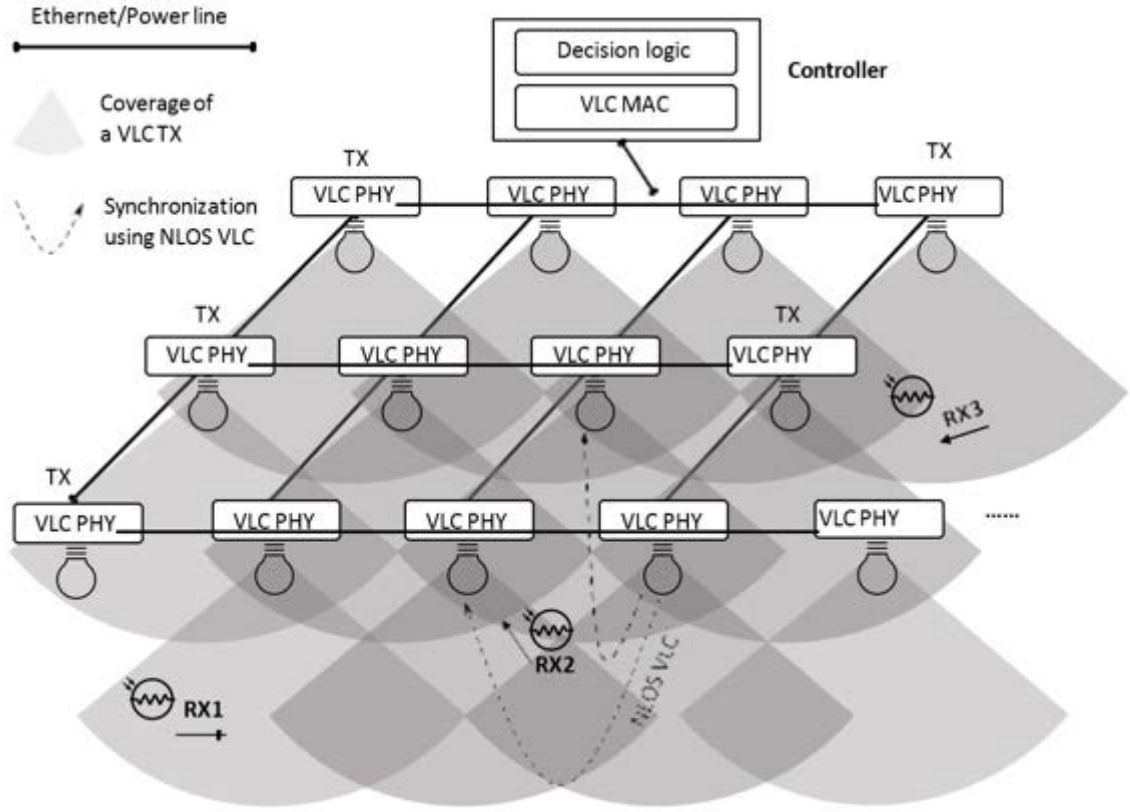


Lighting densification

- Creation of smaller cells to increase network capacity and efficiency (cell-free communication)
- Uniform illumination to increase user comfort offers more dense deployment of light sources (lighting densification)

DenseVLC

- TXs: transmit synchronized signals for distributed MIMO
- RXs: receive signals and measure channel



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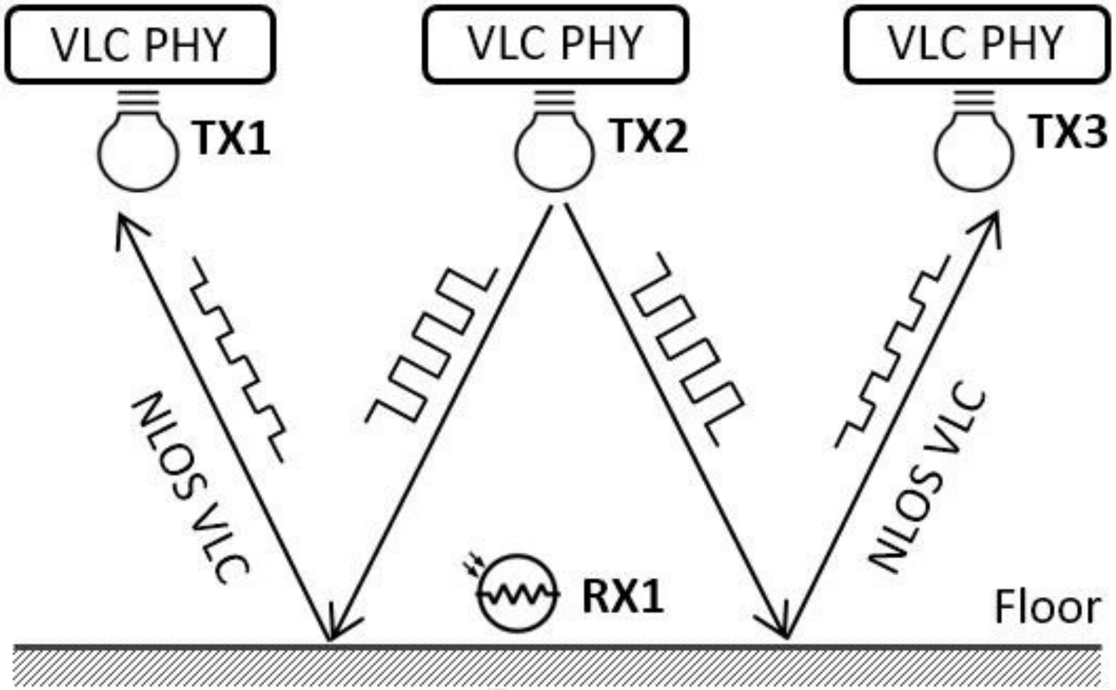
Waveform-level synchronization

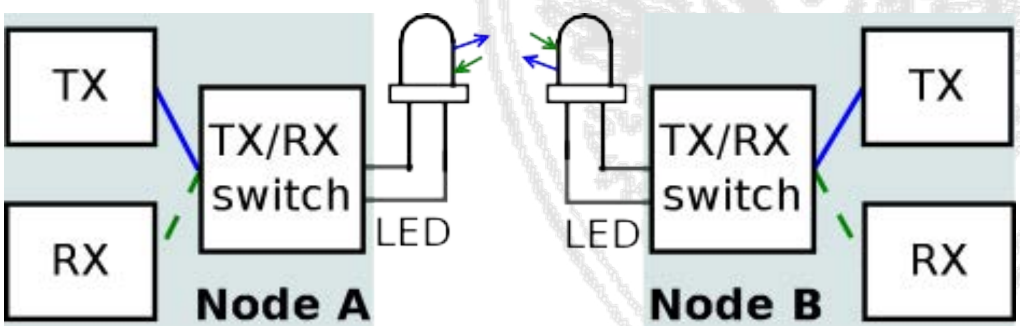
- Traditional synchronization methods have insufficient accuracy
- Possible solution: synchronization via non-line-of-sight pilot signals.

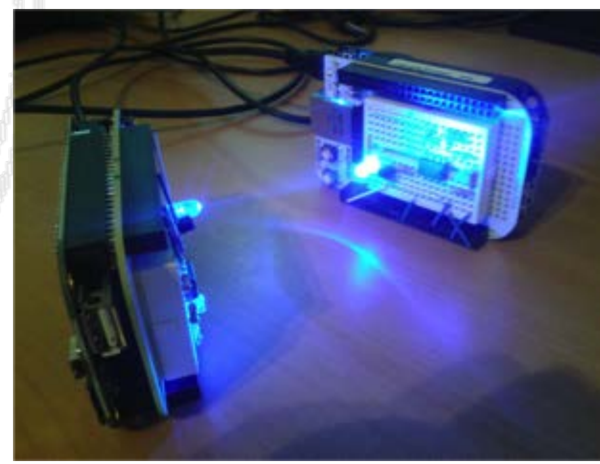


Other VLC architectures

LED-to-LED Communication

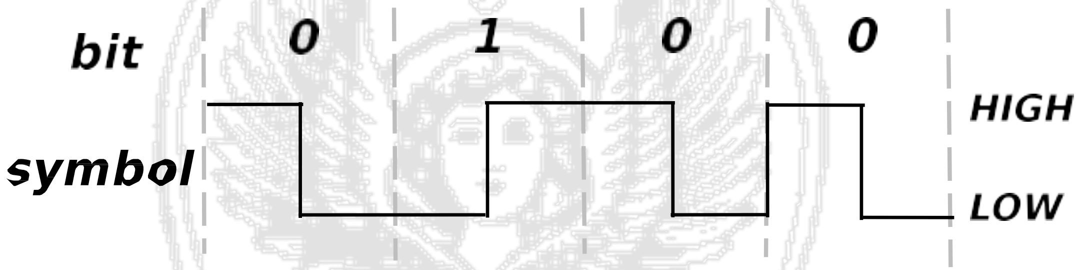
- The front-end transceiver reuses a single LED for both transmission and reception
  - Only one microcontroller and one LED
  - cost-effective approach
  - applications where energy and form factor are fundamental





Enabling bidirectional transmission

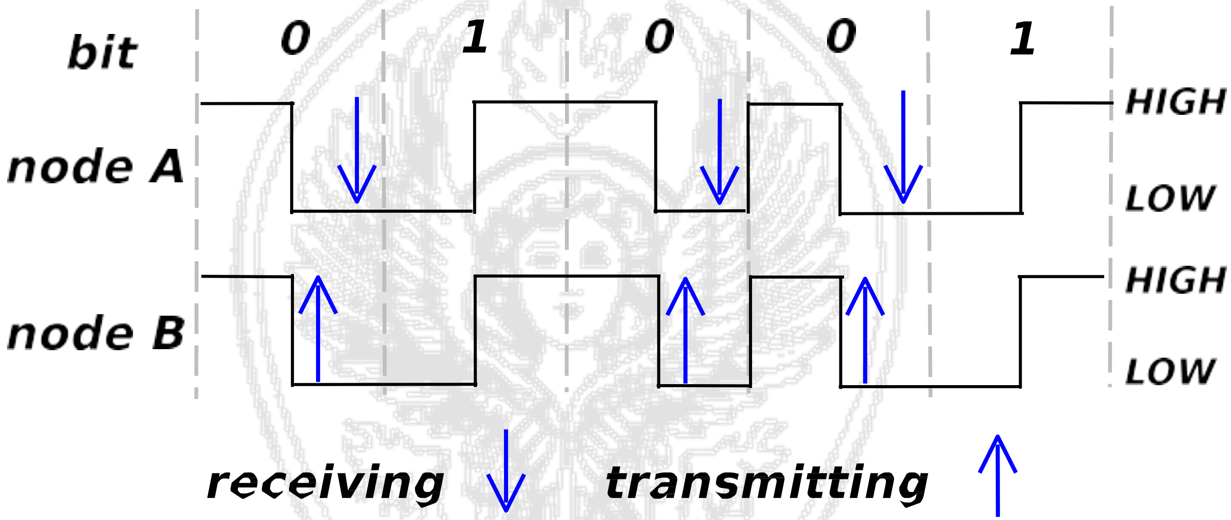
- On-Off Keying (OOK) modulation is greatly adopted in VLC
  - Binary information is mapped to symbols HIGH and LOW
  - Manchester Run-Length Limited (RLL) code



- A node normally does not need emit light when it transmits a symbol LOW
  - can it receive data during these symbols ?

Intra-Frame Bidirectional Transmission

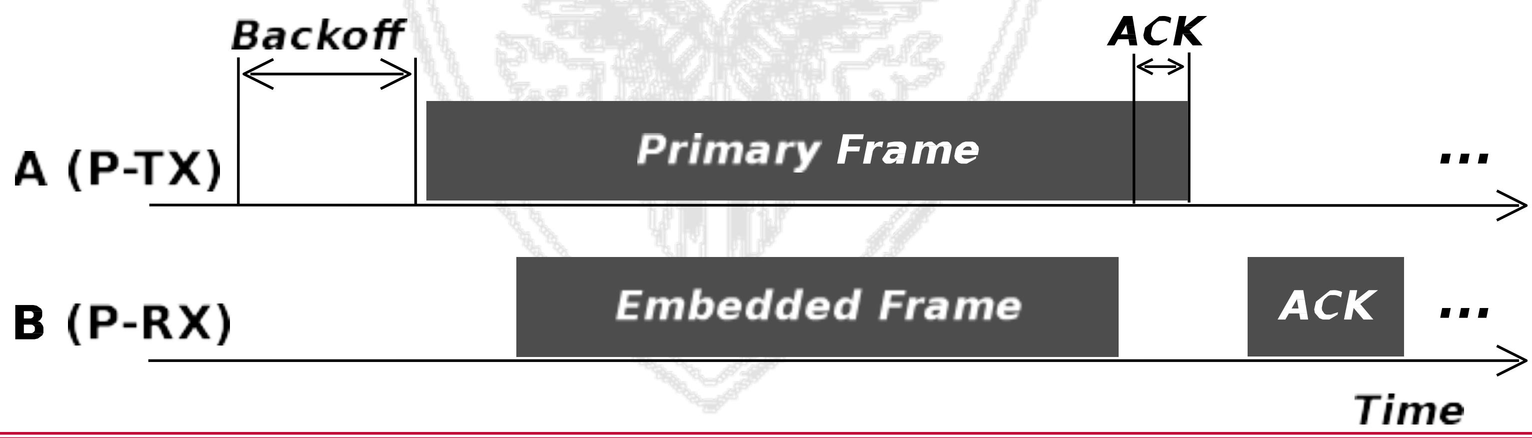
- Exploit the transmission period of a LOW symbol
  - to enable an embedded channel



- How to predict an incoming LOW symbol?
  - Has received a symbol HIGH in current slot
  - The HIGH symbol is the first part of a modulated bit

CSMA/CD-HA MAC Protocol

- Carrier Sensing Multiple Access / Collision Detection & Hidden Avoidance (CSMA/CD-HA)
  - Exploit bidirectional transmissions to boost throughput
  - Reduce the hidden-node problem
- Hidden-node collision: P-RX transmits while receiving P-TX can detect collision if P-RX stops transmission
  - The P-RX will stop sending data if it receives HIGH-HIGH for a few times, due to the collision from hidden nodes.



Network with Hidden Nodes

Setup

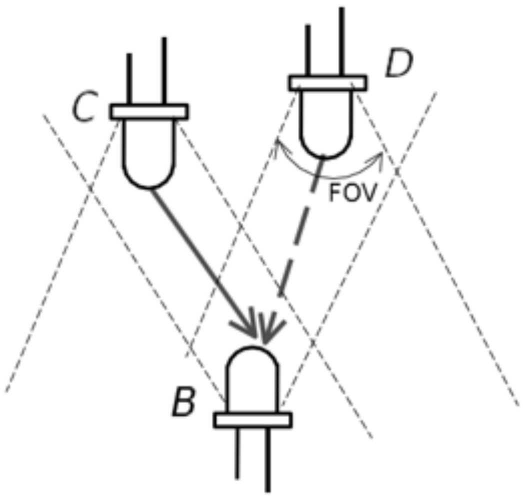
Nodes C and D send data to node B

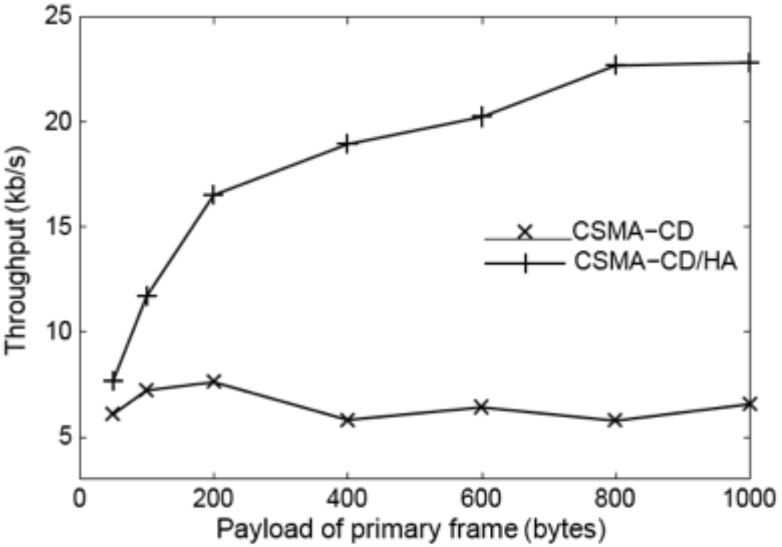
Nodes C and D can not hear each other (hidden nodes)

Results

Throughput can be improved by up to 300%

Collisions due to hidden-node are reduced greatly





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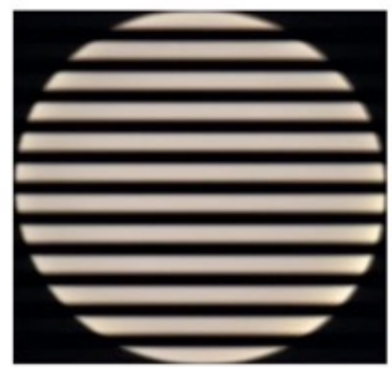
LED-to-Camera Communication

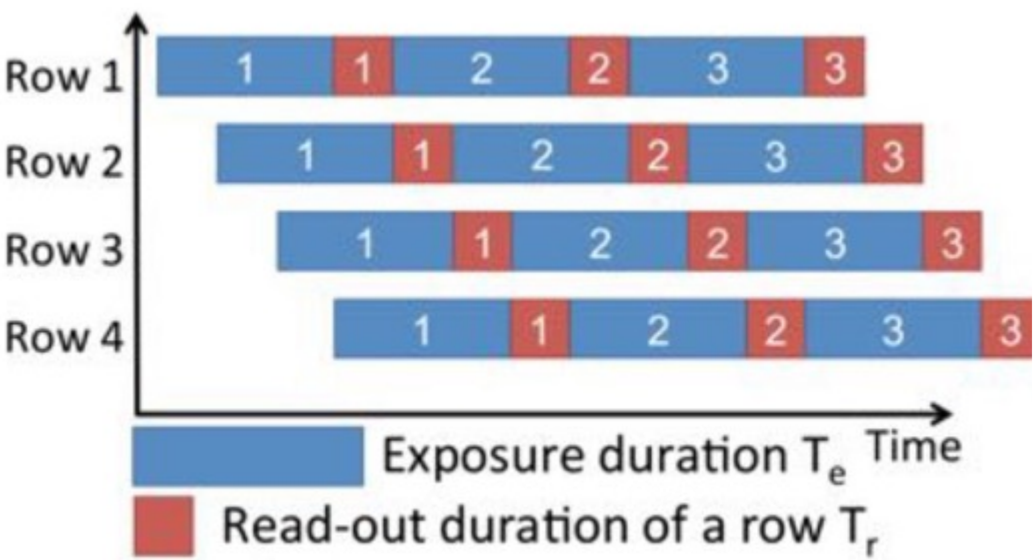
- Global Shutter vs. Rolling Shutter

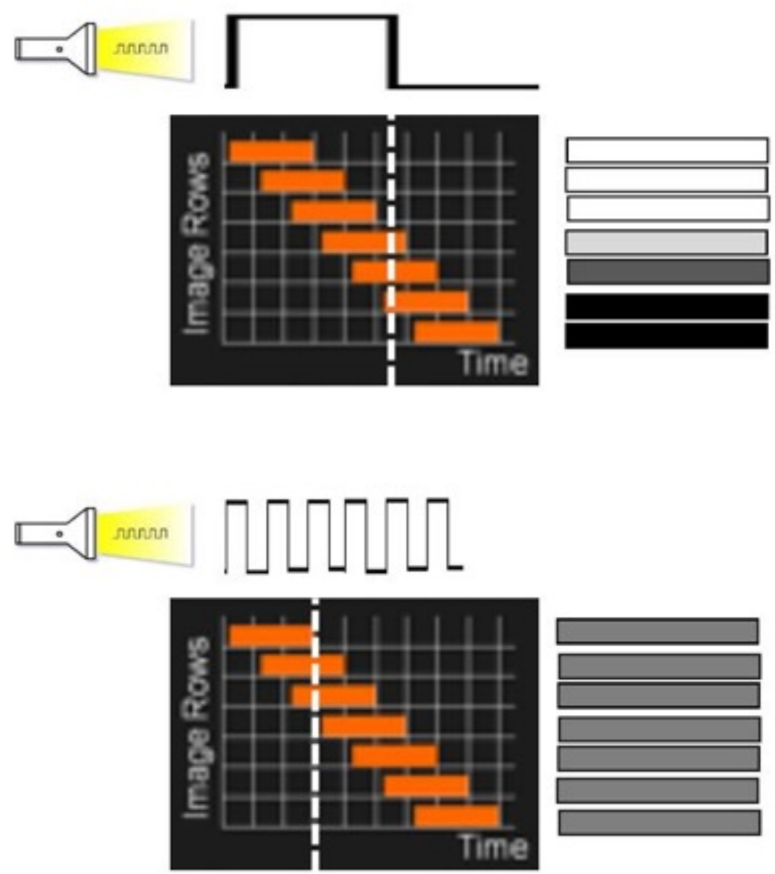


- Rolling shutter: a picture is taken row by row

Step 1: Minimize exposure time

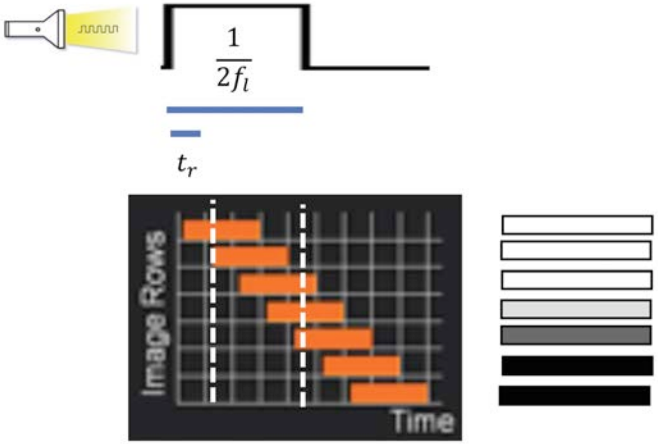
- To increase the modulation frequency, use the shortest possible exposure time
  - Symbol duration > 2*(T_e + T_r)





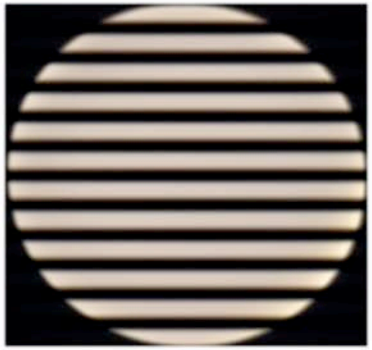
Step 2: optimize number of rows

- To reduce the number of rows per symbol, increase the modulation frequency f_l

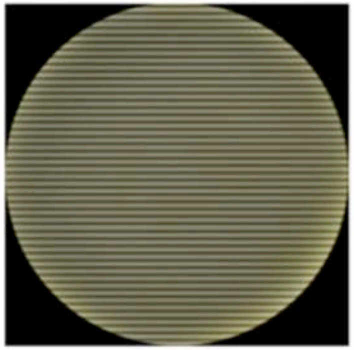


Assuming $t_e << t_r$: $w = \frac{1}{2f_l}\frac{1}{t_r}$

where w = symbol width

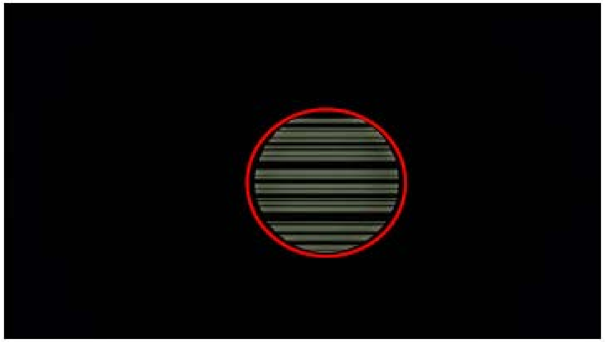


Carrier frequency 1 KHz

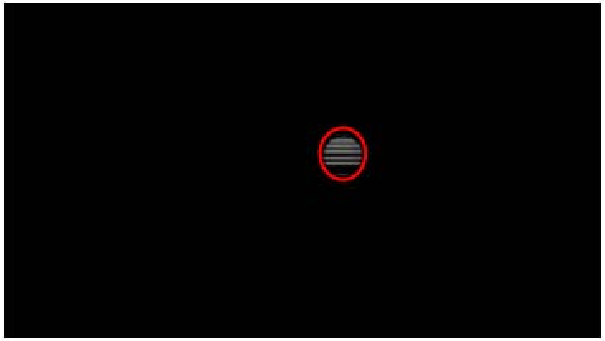


Carrier frequency 5KHz

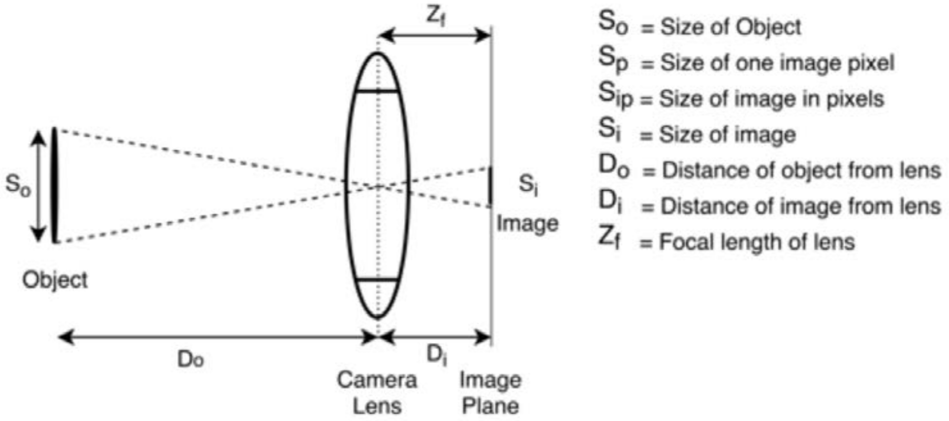
Step 3: overcome the effect of distance



50 cm



200 cm



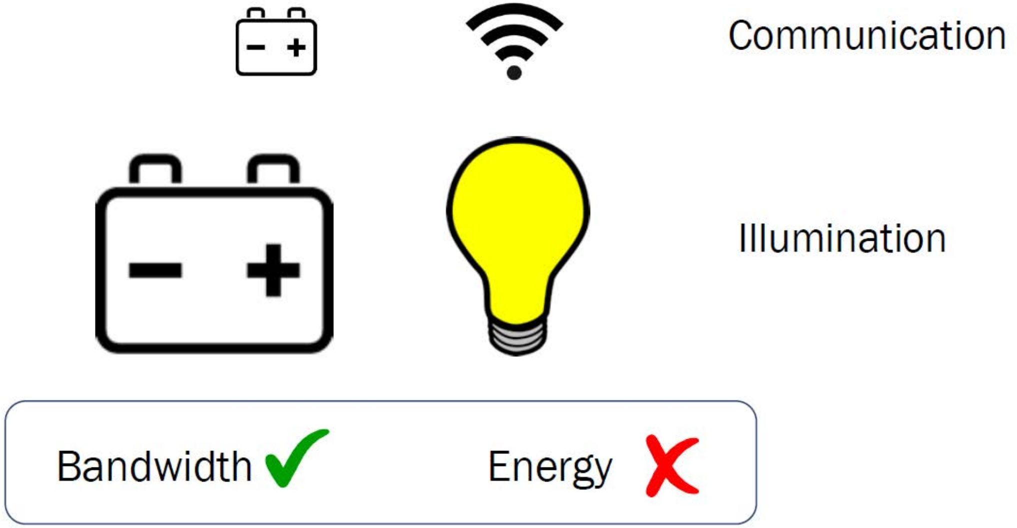
total number of rows in image

$$N_s = \frac{S_0 Z_f}{D_0 S_p} f_l t_r$$

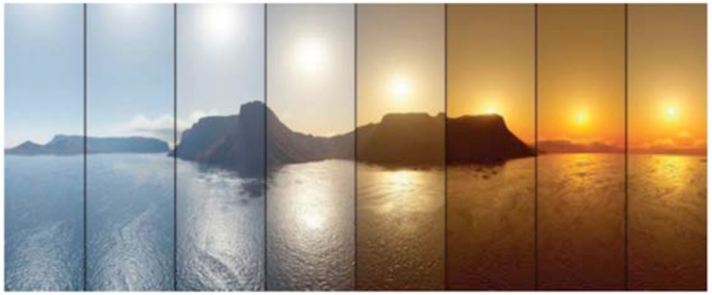
number of rows per symbol

Backscattering & Passive Communication

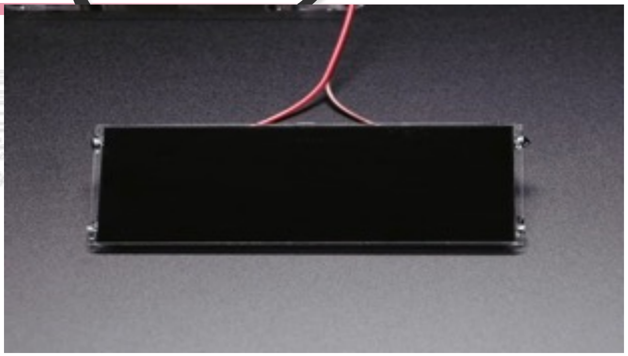
- Active light communication: limitations

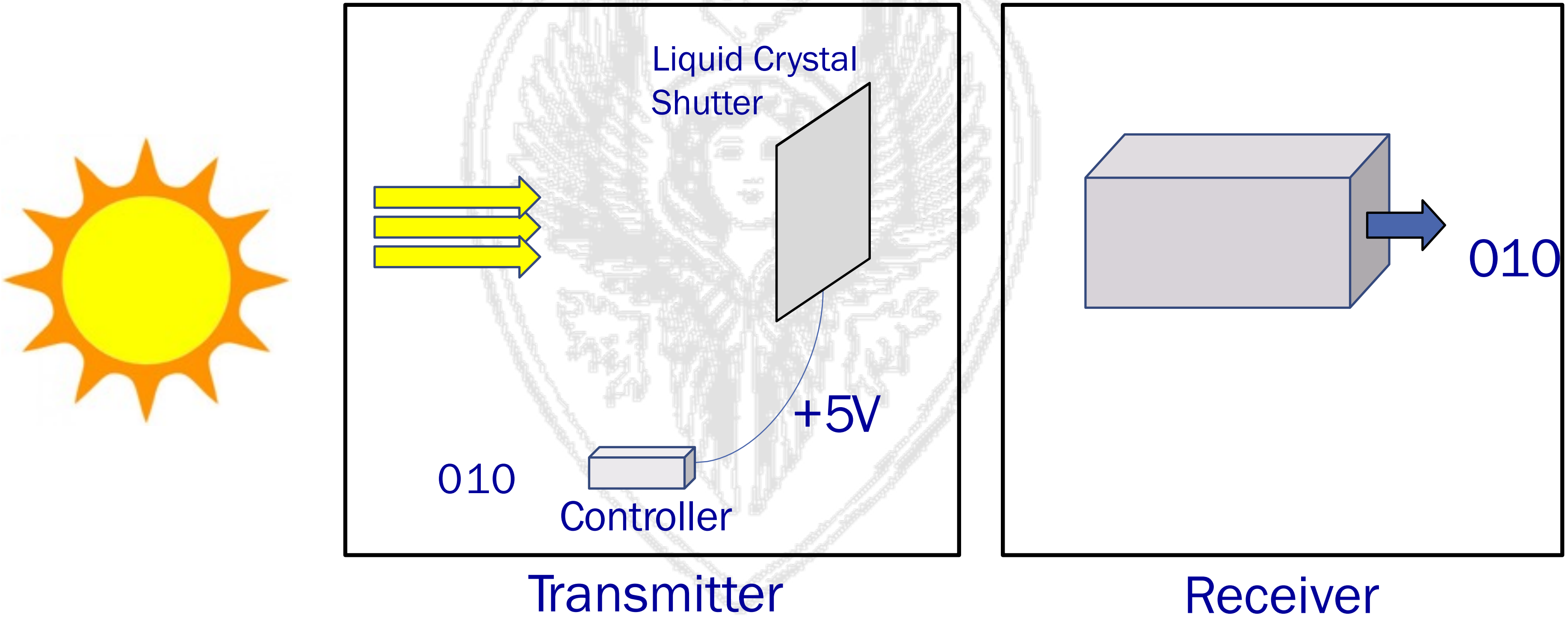


- How about passive light?
  - more pervasive
  - more energy



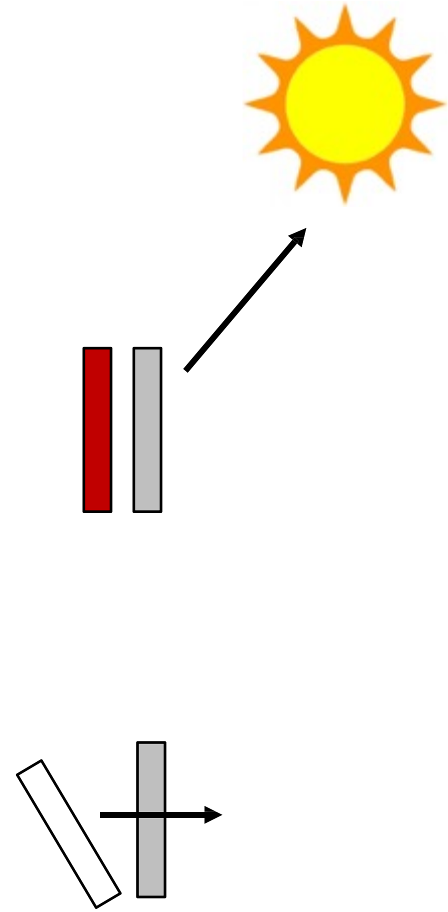
Liquid Crystal Shutters (LCDs)





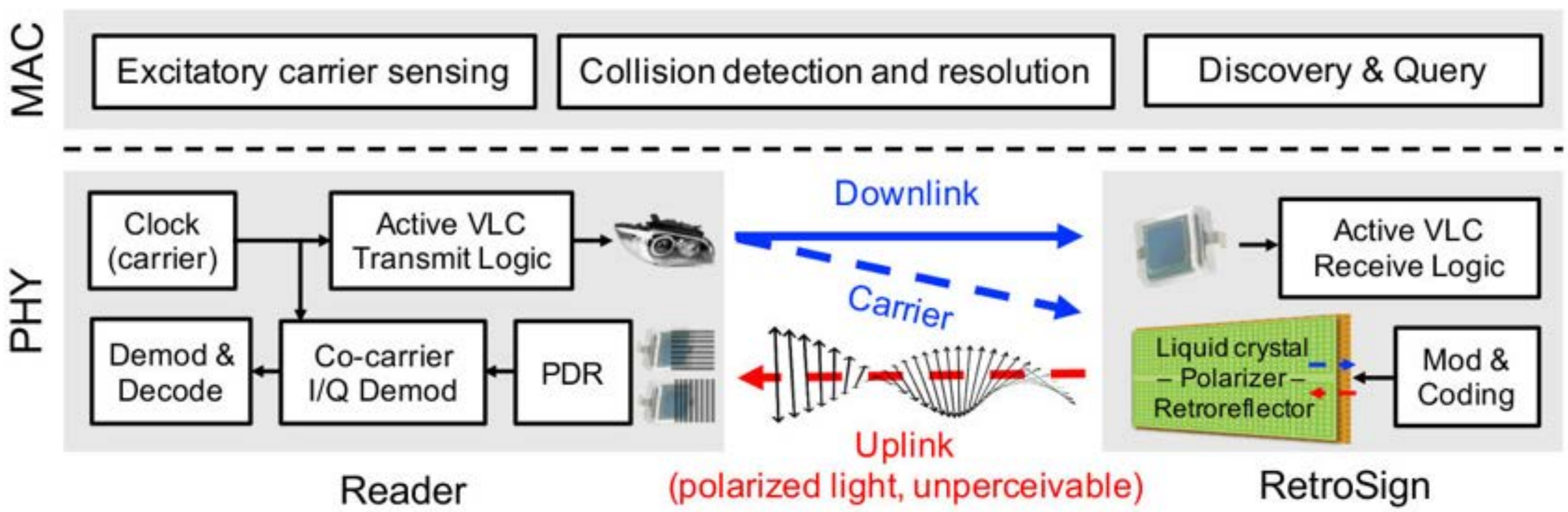
Backscattering light

- Passive VLC
- Source might be both solar or artificial



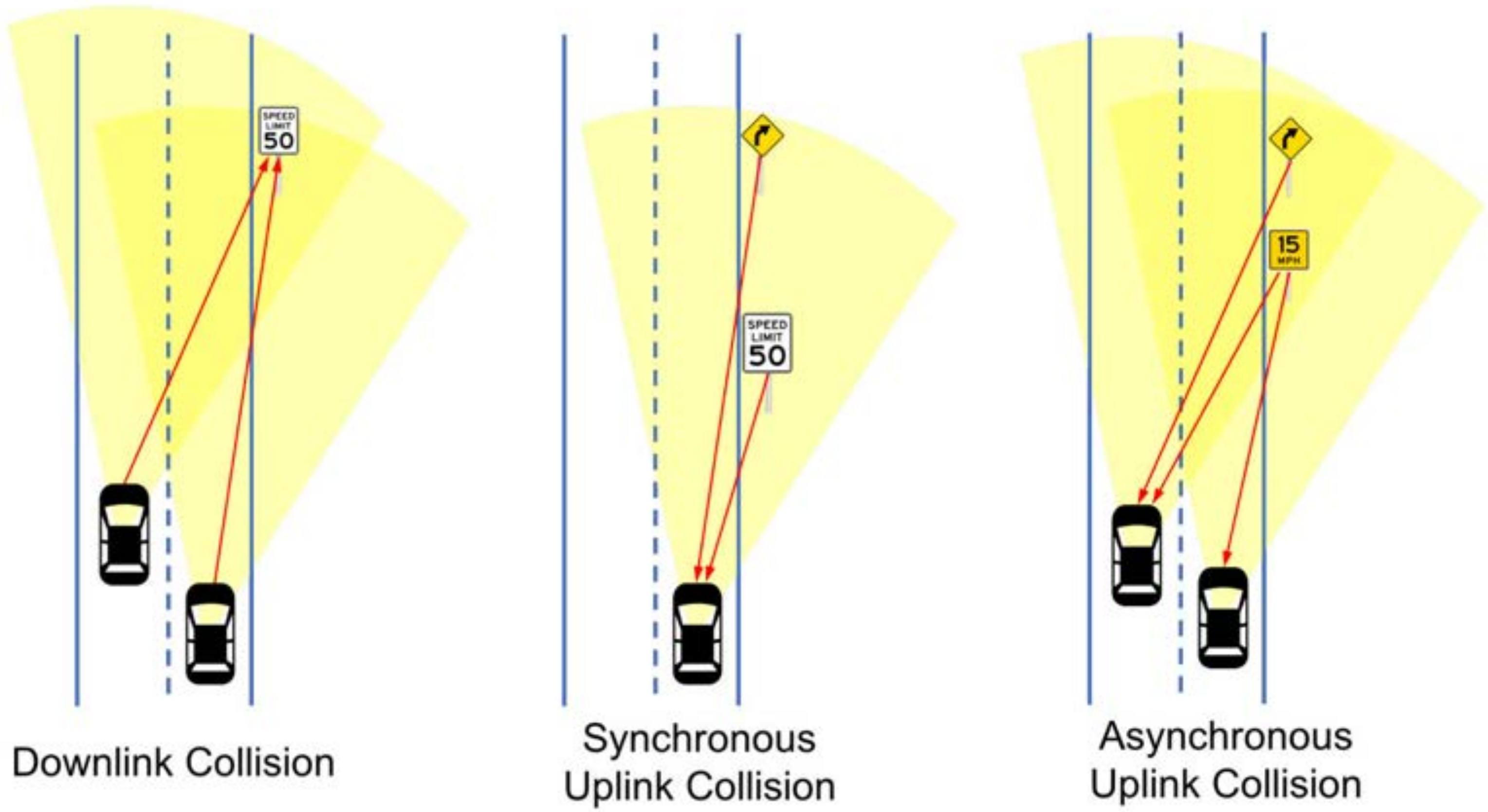
Road Signs for I2V Networking

- Renovates conventional road signs to convey additional and dynamic information to vehicles
- While keeping intact their original functionality
- Exploit the retroreflective coating of road signs



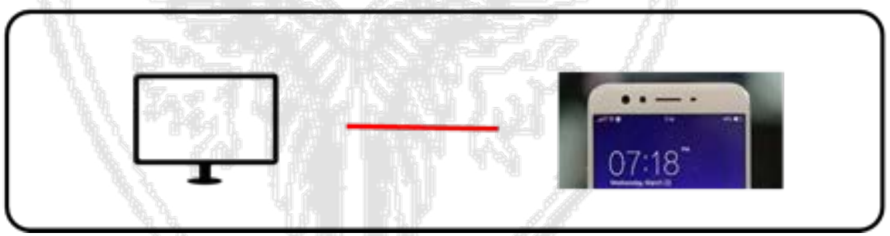
Collision scenarios

- Not so simple…



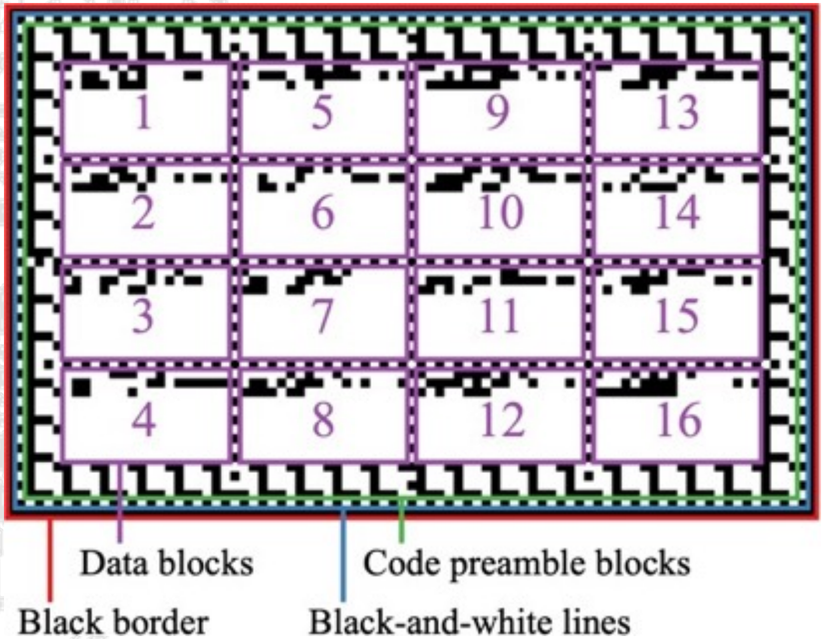
Beyond traditional VLC

- Screen to camera communication!



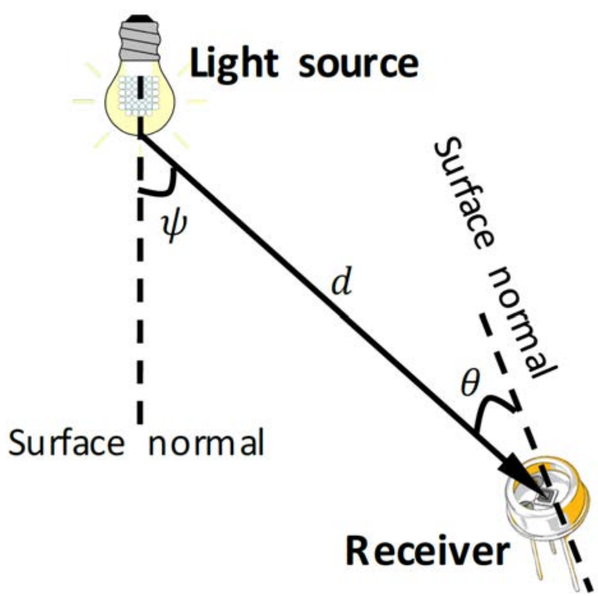
Screen-to-camera communication

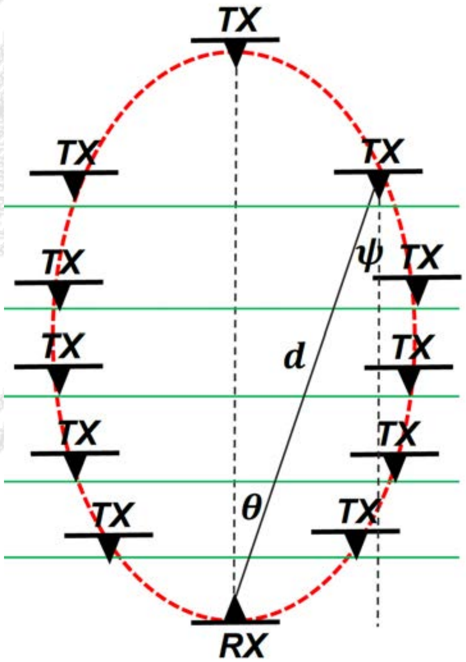
- Double the frame rate of the movie and encode information by mixing colors



Localization using LEDs

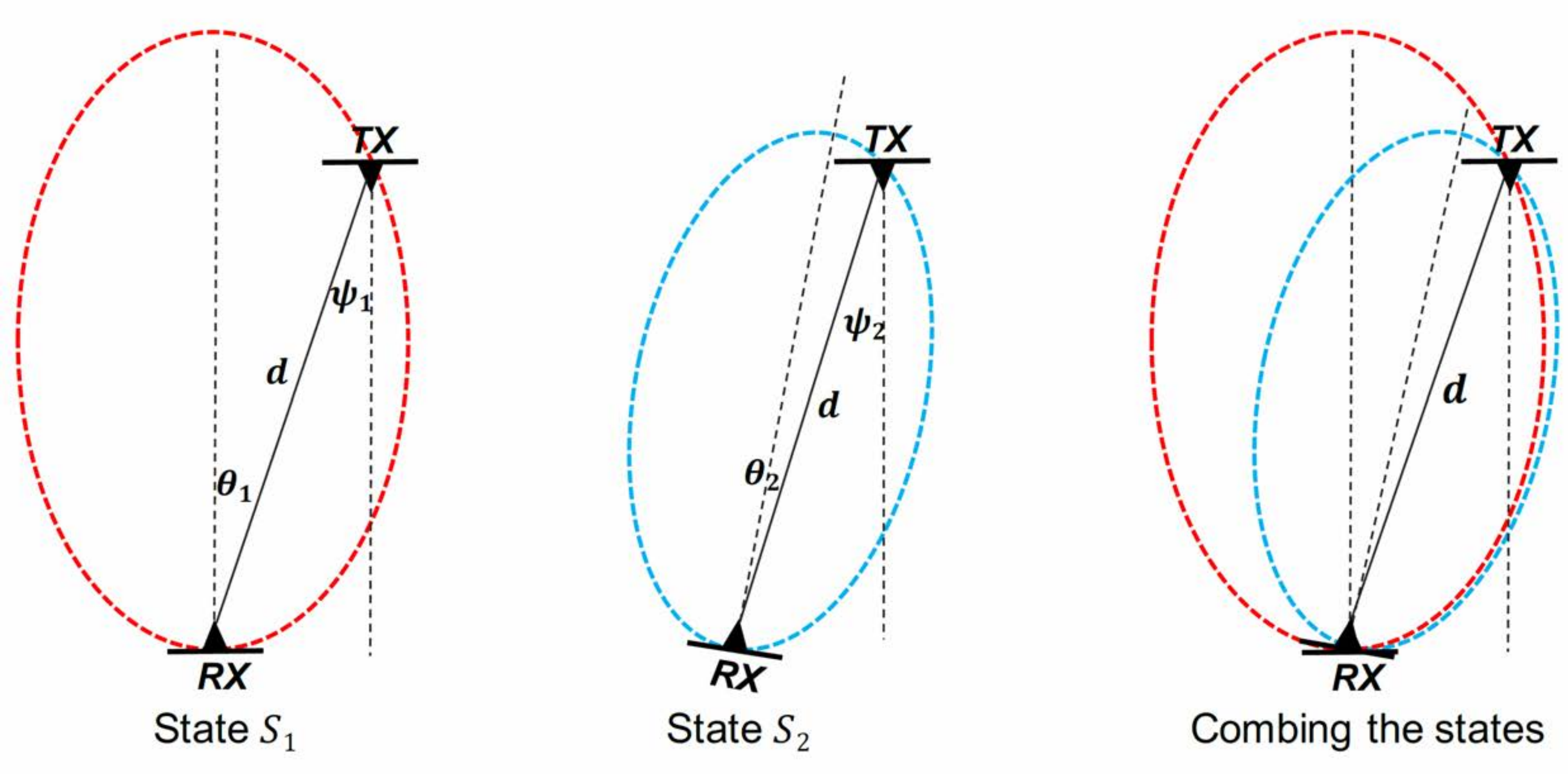
- Fix the TX's orientation and move it at different perpendicular distances from the RX
  - provides two locations where the measured received power is Pr
  - All these locations form an iso-contour where the received power is the same





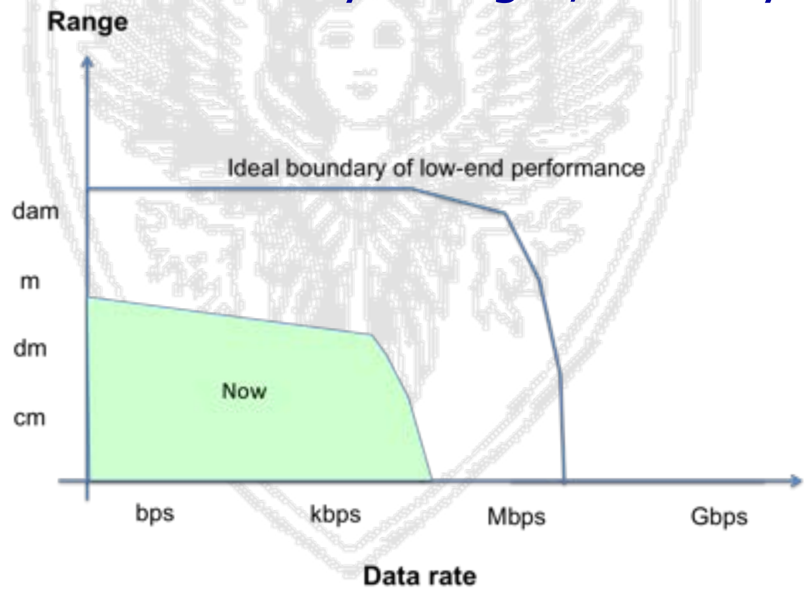
Localization using LEDs

- Received signal strength at the RX depends on three parameters: distance, irradiation angle and incidence angle. Lambertian radiation patterns, remember?...



Conclusions

- VLC: reasonable performance with cheap hardware
  - Data rate order of Mbps, range of meters
  - New modulation, coding and multiple access schemes, etc.
  - Interference avoidance in dense deployments, handover, etc.
  - Accurate localization algorithms
  - Challenges: interference by sunlight, mobility vs. performance



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Thank you!

Questions?