Multi-Element Mobile Visible Light Communication for Smart Cities

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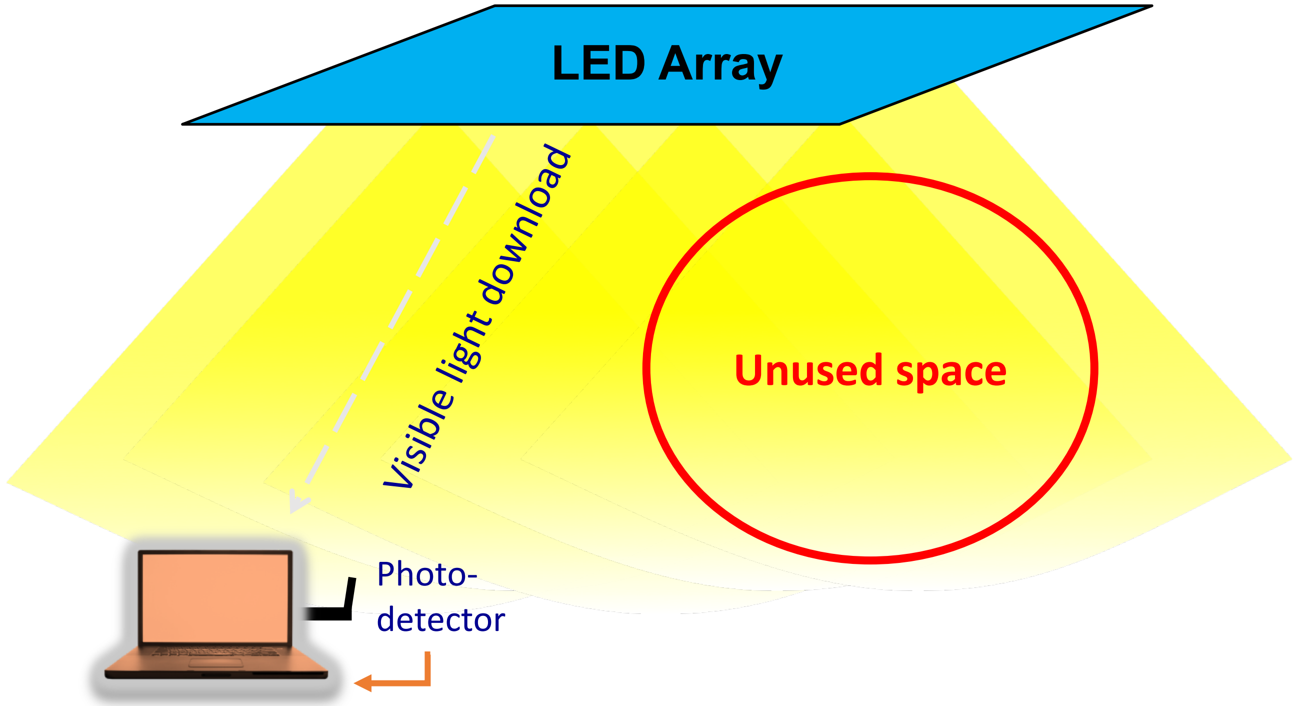
Visible Light Communication

- **Transmission: How to use a visible light source which, in addition to illumination, can transmit information using the same light signal?**
- **Reception: How to detect the received data-carrying light signal and decode the information?**
- **Goals:**
  - High Communication Range
  - High Data Rate
  - Robust Reception in Mobile Settings
  - Uniform Illumination
  - Low Power Consumption

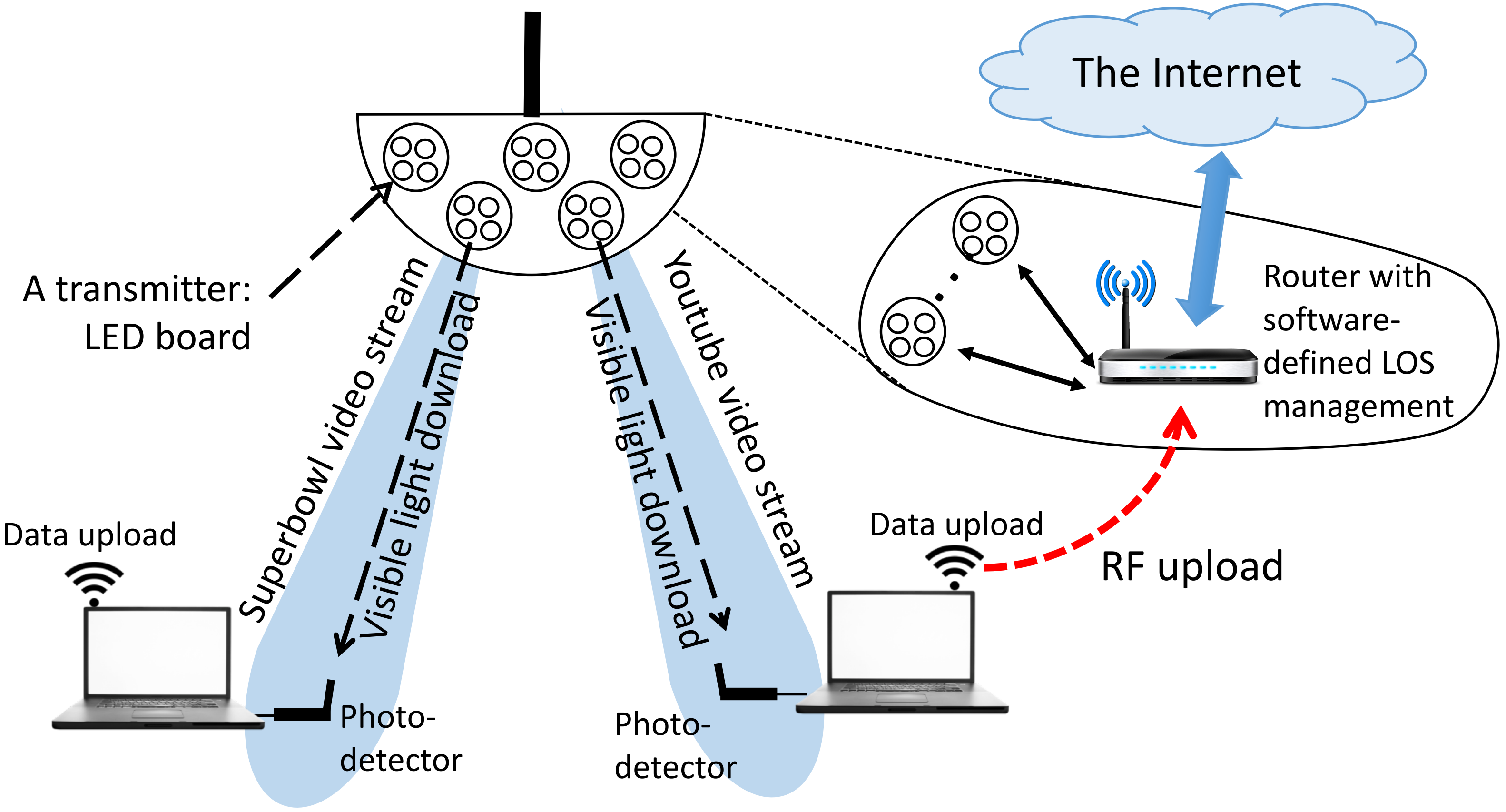
Benefit of Multi-element VLC



Single data stream
Large divergence – for smooth lighting

Multiple data streams
Narrow divergence – for higher spatial reuse
Spherical structures – to retain smooth lighting

Proposed Multi-element VLC Architecture



VLC for Mobiles

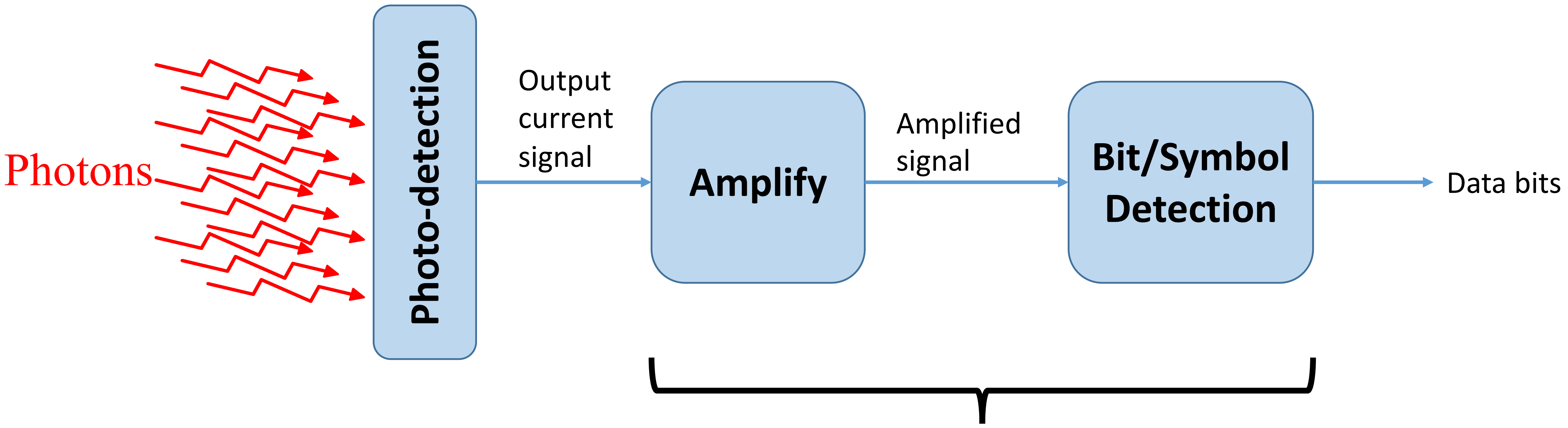
How to design robust receivers?

VLC for Mobiles

- Existing VLC solutions use receivers with large FOV but a small aperture area.
- Small aperture area allows high speed reception.
- But, can easily be blocked by a finger!

- How can we increase the reception aperture area while keeping the reception rate high?

VLC Receiver Design



We re-worked this part while increasing the photo-detection aperture area.

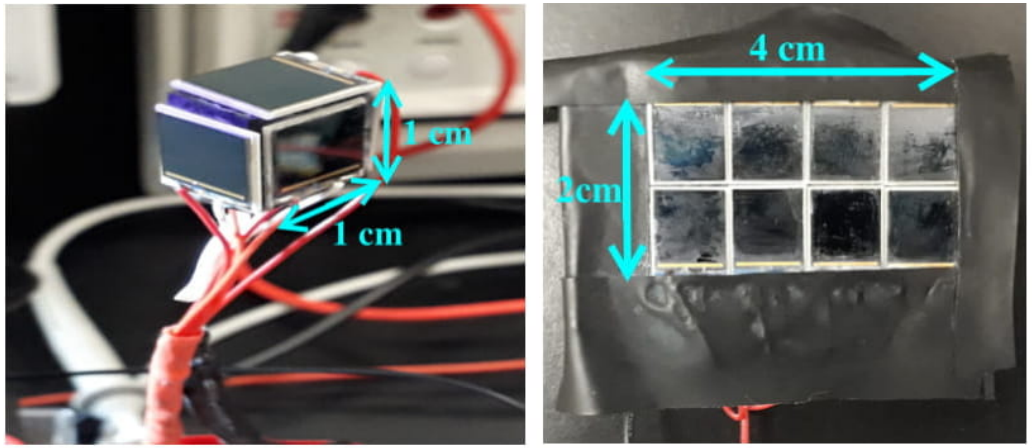
VLC Receiver Design: Photo-detection

- Each APD
  - Has 1cm^2 aperture area
  - Costs $50

- 5-8 APDs
- Can be arranged conformal to the surface of the mobile device

IMPORTANT CHARACTERISTICS OF FDS1010

Specifications	
Wavelength Range, λ	350 – 1100nm
Peak Responsivity, $max[\mathcal{R}(\lambda)]$	0.725A/W
Active Area per PD, A	100mm^2
Rise/Fall Time, t_r/t_f ($V_B = 18V$)	18ns
Dark Current ($V_B = 18V$)	80μA
Capacitance, C_J ($V_B = 18V$)	169.2pF
Maximum Tolerable Reversed Biased, $V_{B,max}$	25V
Maximum Output Photocurrent, I_o	10mA
Maximum Optical Input Power, $P_{i,max}$	10mW

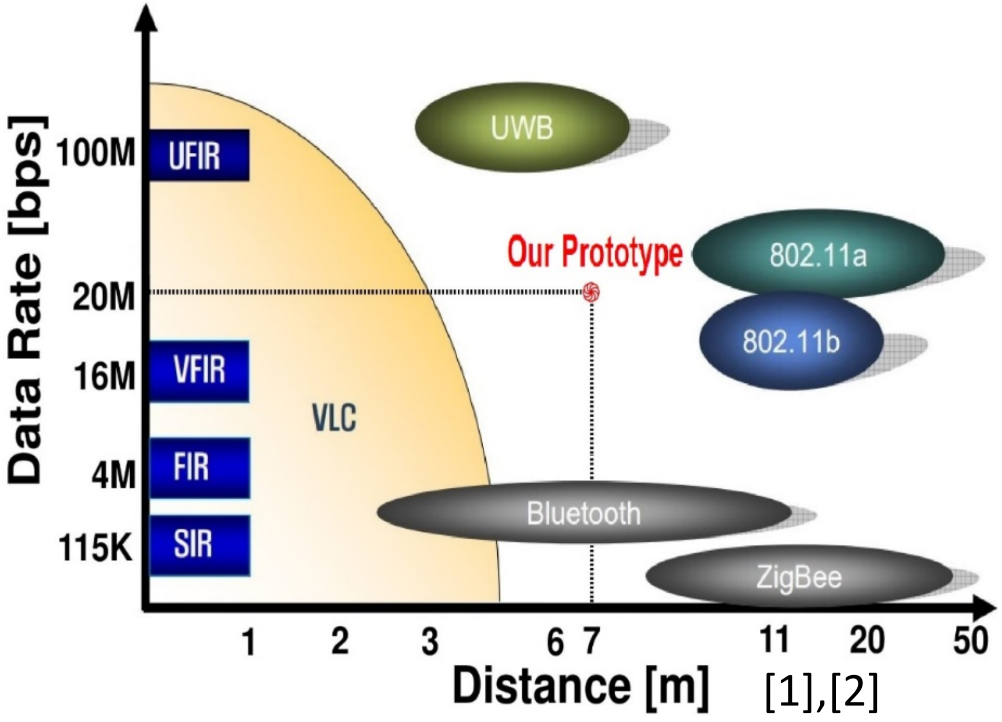


(a) (b)

VLC System Performance

- Max Range $\approx 7\ m$
- Max BW $\approx 20 - 26\ MHz$

	R	BW	FOV	Packet Loss Rate
Our Prototype	7.1 m	20 MHz	360°	10^{-6}
Pure LiFi-X [23]	1.8 m	42 MHz	60°	$\approx 3.4 \times 10^{-5}$
[21]	2.4 m	10 KHz	10°	10^{-2}
[20]	50 m	50 KHz	75°	3.2×10^{-4}
Thorlabs [24]	0.45 m	12 MHz	150°	$\approx 10^{-4}$



[1],[2]

IEEE ICC 2019

[1] E. T. Won, D. Shin, D. Jung, Y. Oh, T. Bae, H.-C. Kwon, C. Cho, J. Son, D. O'Brien, T.-G. Kang, and T. Matsumura, IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs): Visible Light Communication: Tutorial, 2018.

[2] S. Rajagopal, R. D. Roberts , and S. Lim, "IEEE 802.15.7 visible light communication: modulation schemes and dimming support," IEEE Communications Magazine, vol. 50, no. 3, pp. 72–82, March 2012.

Summary

- Efficient VLC system design and challenges
- A prototype indoor VLC system that is made of off-the-shelf components, and is scalable and suitable in an office environment.
  - 20 Mbps, 7 m and BER < 10^{-5} under intense vibration
- A multi-photodetector (PD) array VLC receiver design, conformal to surfaces of IoT shapes (e.g., laptop, TV monitor, or VR headset) with large aperture area
- Experimental channel modeling and characterization of vibration effects
- Design for vibrant VLC link with high delay spread and non-zero memory:
  - How to reduce ISI by implementing optimal (MSD) and sub—optimal (DF-APA) algorithms
  - Formulation of ISI effects on wide FOV receivers in vibrant VLC channels

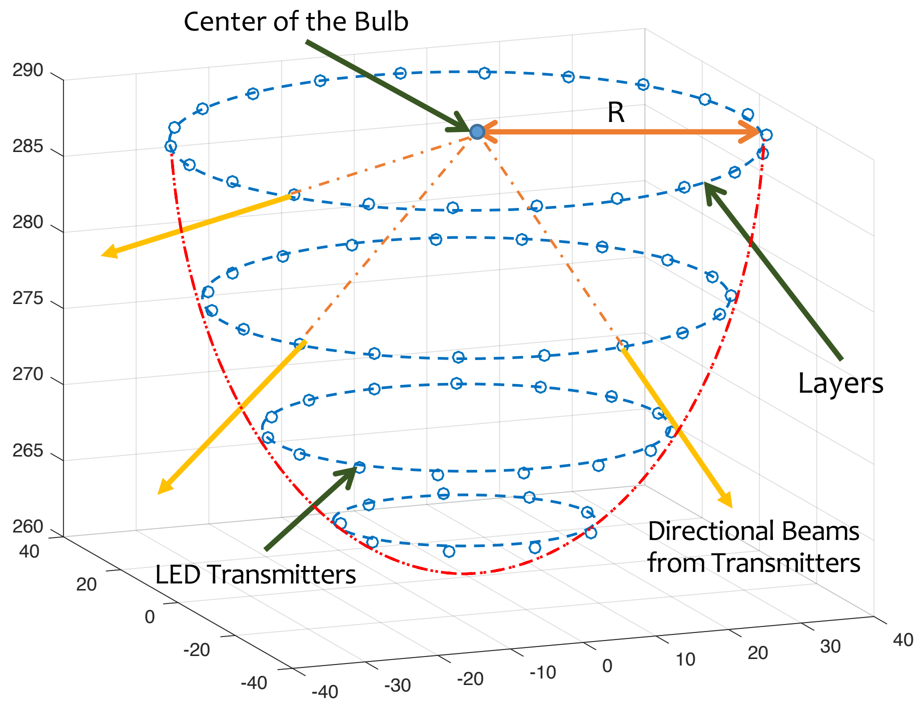
VLC for Many Mobiles

How to associate VLC beams to mobile users and tune them

-- while having "good" illumination?

Proposed Hemispherical Bulb

- **The LEDs are mounted in the bulb in Circular Layers**
- **Multiple LEDs can be assigned to a particular user but no LED is assigned to more than 1 user**
- **A variable, ϵ_{mu}, defines the association between LED m and User u**



$$\epsilon_{mu} = \begin{cases} 1, \text{if LED } m \text{ is associated with user } u. \\ 0, \text{otherwise.} \end{cases}$$

UCF

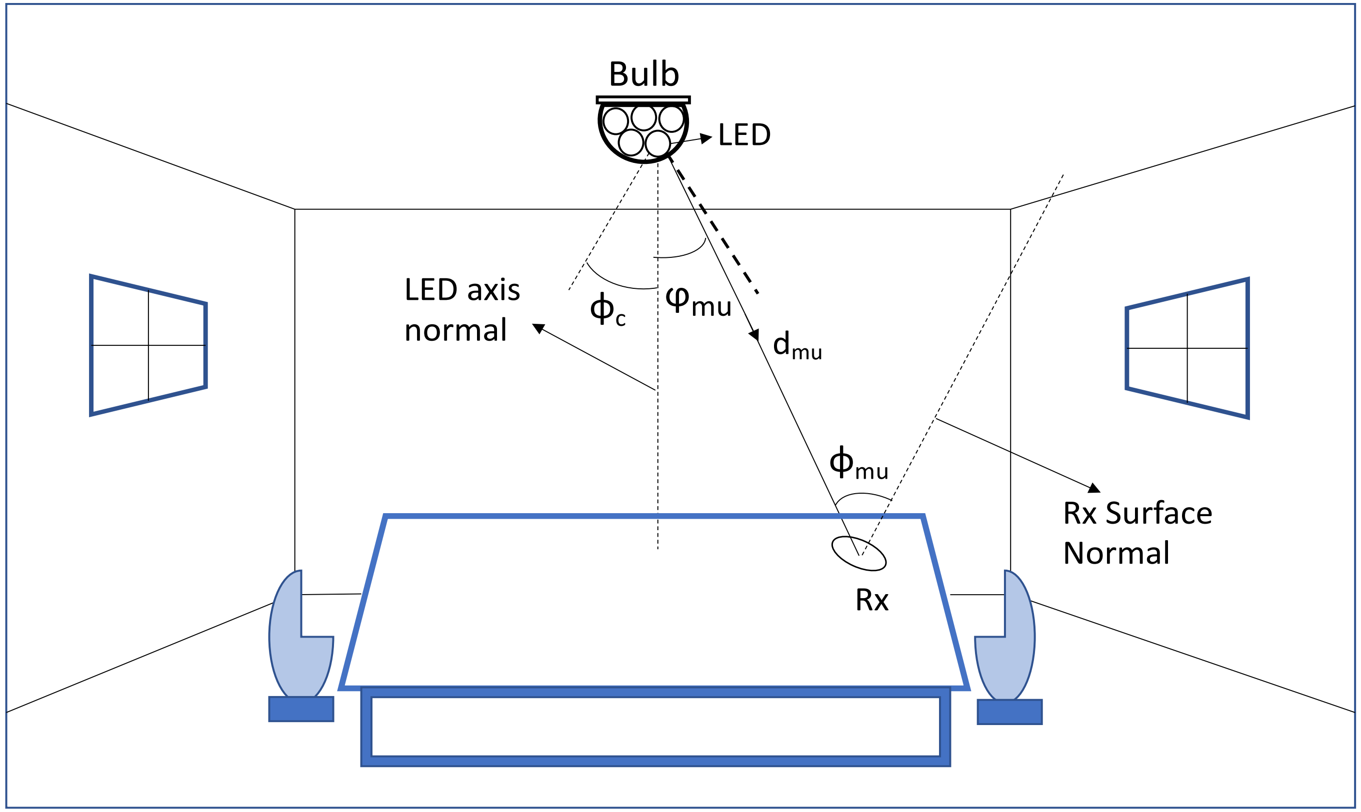
VLC Channel Model

$$h_{mu} = \begin{cases} \frac{A_u}{d_{mu}^2} Q_0(\varphi_{mu}) \cos(\phi_{mu}) & , 0 \leq \varphi_{mu} \leq \phi_c \\ 0 & , \varphi_{mu} \geq \phi_c \end{cases}$$

Channel between the m^th LED and the n^th User

$Q_0(\phi_{mu})$ → Lambertian radiant intensity

Φ_c → LED divergence angle



The Problem In Hand

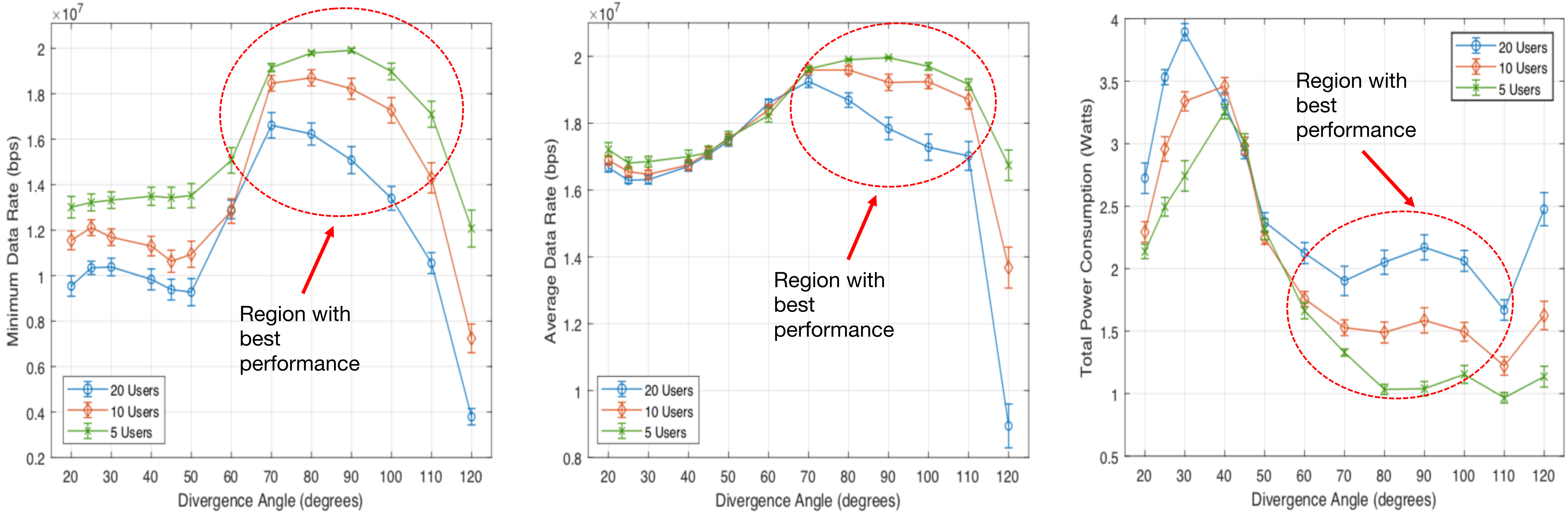
Several things to consider

- **Total power consumption of the system**:
  There can be a large number of IoT devices in the network
- **Data rates of each user in the system**:
  Ensuring a minimum data rate for each IoT device is critical
- **Illumination uniformity**:
  We also should not forget about the lighting quality!

Problem Solution

- Properties of the formulated optimization problem
  - Non-convex
  - Mixed-integer
  - Non-linear
- Our proposed two-stage heuristic solution
  - First stage: A ‘Nearest User Assignment’ (**NUA**) approach is implemented to determine the value of ϵ_{mu}
  - Second stage: Using the LED-user associations from the value of ϵ_{mu} found in stage 1, we optimize the LEDs’ power allocations

Simulation Results



System analysis for different LED divergence angles

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Summary

- An optimization problem that minimizes the total energy consumed by the multi-element bulb while considering the LEDs' power budget and maintaining illumination uniformity
- Each LED could be for transmission of data to a receiver as well as for increasing the illumination uniformity
- The users' QoS and the LED-user association are considered
  - A minimum data rate of 1 Mbps is maintained in all the scenarios
- Cost-effectiveness is improved significantly for a high number of users

Future Work

- VLC Receiver
  - PCB-based implementation
  - Removing FPGAs out of the way: Integration with laptops or smartphones
  - Scaling the aggregate aperture area at the receiver:
    - Detect and merge
    - Advanced learning methods
  - Further understanding of the VLC channels in a casual office/indoor settings: Shakes, human movements, reflections
- Multi-element Bulb
  - Larger room size with more users (as in airports or hospitals)

- Deployment and testing at Northumbria

Words for GEFI

- VLC is more needed and maturing as technology, e.g., LiFi
- Testbeds are needed to proliferate the VLC research innovations
  - Integration with cellular and WiFi systems is necessary
  - Transceivers with VLC and radio capability are worthy investments

Thank you!