Internet of Radio Light
VLC Receiver

Dr. Bastien Béchadergue
bastien.bechadergue@oledcomm.net

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2. **VLC Receiver Proposed**
3. **Performance Evaluation**
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Content

1. Background and Objectives

2. VLC Receiver Proposed

3. Performance Evaluation

4. Conclusions

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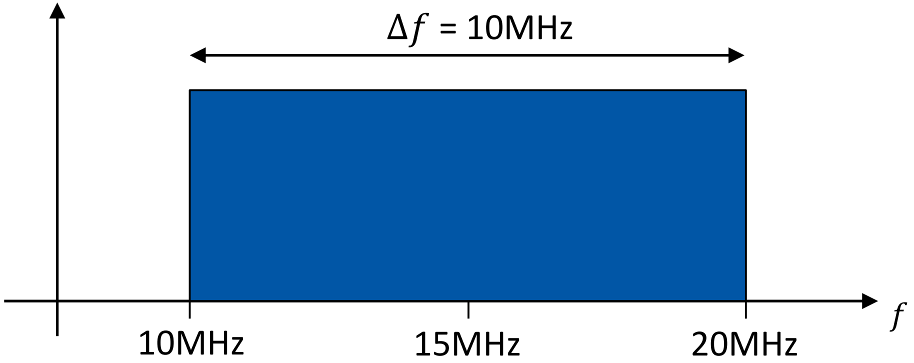
Background and Objectives

From the Transmitted Signal…

- Transmitted signal = OFDM signal with subcarriers spread over a fixed channel.
- Channel characteristics:



- **Conclusion**: The VLC receiver must have a flat electrical bandwidth from 10MHz to 20MHz.

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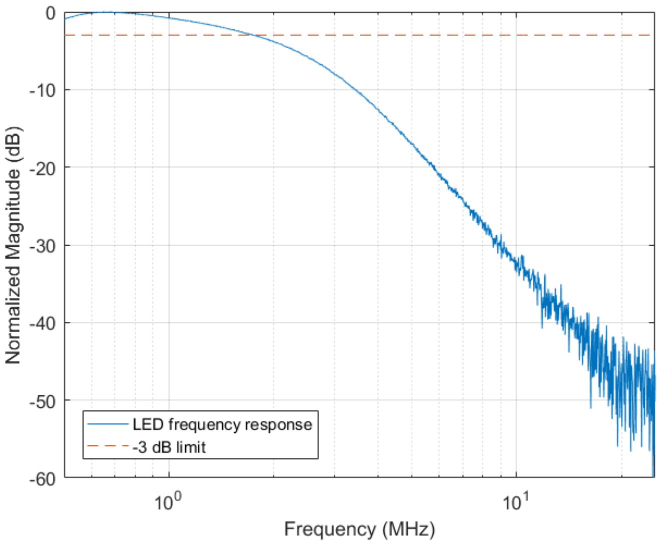
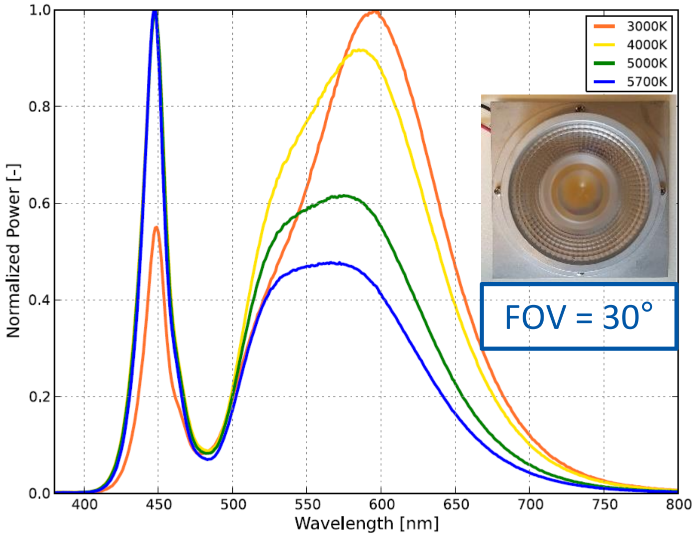
Background and Objectives

…and Light Source Characteristics…

Electrical bandwidth



Optical bandwidth and Field-of-Emission



- **Conclusion**: The VLC receiver must detect white light with high sensitvity and take into account the light source bandwidth.

Background and Objectives

…to the Received Signal

- On the receiver side, the main goal is to optimize the signal-to-noise ratio (SNR), defined as:

$$\mathrm{SNR} = \frac{S}{N},$$

- Which means optimizing the received signal power S, defined as:

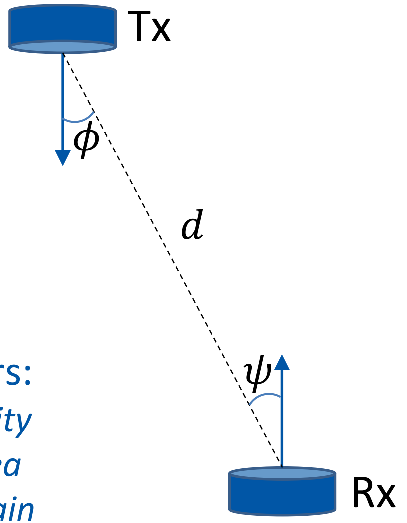
$$S = \left[\frac{(m+1)P_t}{2\pi d^2}\cos^m\phi\,\cos\psi\,\gamma A_r g(\psi)\right]^2$$

Light source parameters

Link geometry

Receiver parameters:

- $\gamma \rightarrow$ *Photosensitivity*
- $A_r \rightarrow$ *Sensitive area*
- $g(\psi) \rightarrow$ *Optical gain*



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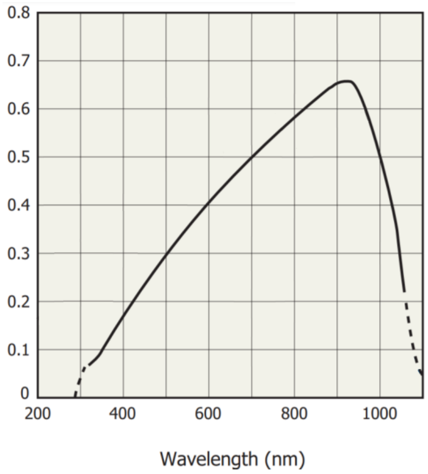
Background and Objectives

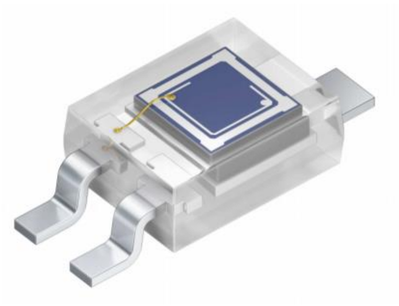
Main Parameters of a Photoreceiver for VLC

Photosensitivity



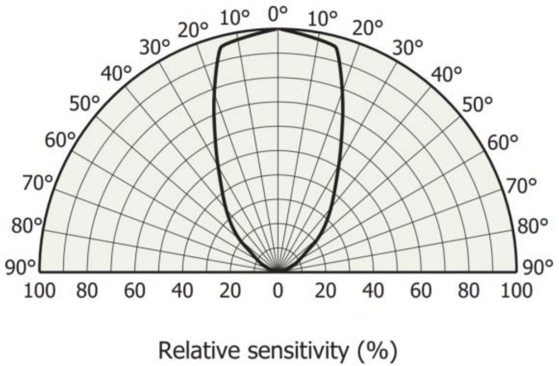
- Non-null sensitivity in the visible wavelength range needed.
- The higher the better!

Sensitive Area



- The larger the better…but…
- ↗ sensitive area → ↗ capacitance.
- ↗ capacitance → ↘ bandwidth
- Tradeoff on the sensitive area.

Optical Gain



- ↗ gain → ↗ received power.
- ↗ field-of-view → ↗ coverage.
- ↗ gain → ↘ field-of-view.
- Tradeoff on the gain pattern.

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Background and Objectives

Off-the-Shelf Photoreceiver Benchmark

Reference	Technology	Max. sensitivity	Sensitive area	Bandwidth
Thorlabs PDA100A	Si PIN	0.72 A/W @ 960 nm	75.4 mm²	DC – 11 MHz
Thorlabs PDA8A2	Si PIN	0.56 A/W @ 820 nm	0.5 mm²	DC – 50 MHz
Thorlabs APD130A2(/M)	Si APD	25 A/W @ 600 nm	0.78 mm²	DC – 50 MHz
Thorlabs APD430A2(/M)	Si APD	50 A/W @ 600 nm	0.03 mm²	DC – 400 MHz
Hamamatsu S12702-04	Si APD	15 A/W @ 800 nm	7.07 mm²	4 kHz – 80 MHz
Hamamatsu S12702-12	Si APD	12 A/W @ 620 nm	7.07 mm²	4 kHz – 40 MHz

Reference photoreceiver

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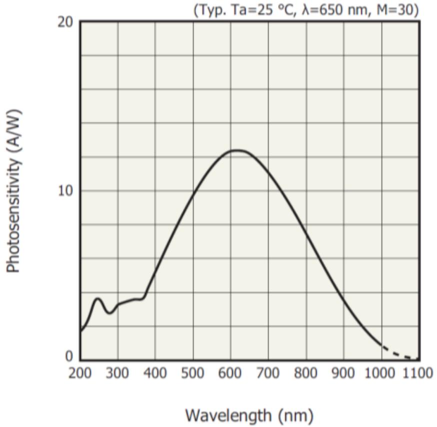
Background and Objectives

S12702-12 Receiver vs Custom-Made Receiver Objectives

- **Main advantages**:
  - Large sensitive area (7.07 mm^2),
  - Matching bandwidth (4 kHz to 40 MHz),
  - High photosensitivity, optimized for visible light,
  - Possibility to add an optical lens or concentrator.
- **Main drawbacks**:
  - Large form factor (90x50 mm),
  - APD needs large bias voltage (> 200V),
  - Very expensive (several 100s €).

Conclusion: The goal is to design a cheap and compact custom photoreceiver based on Si PIN photodiodes.



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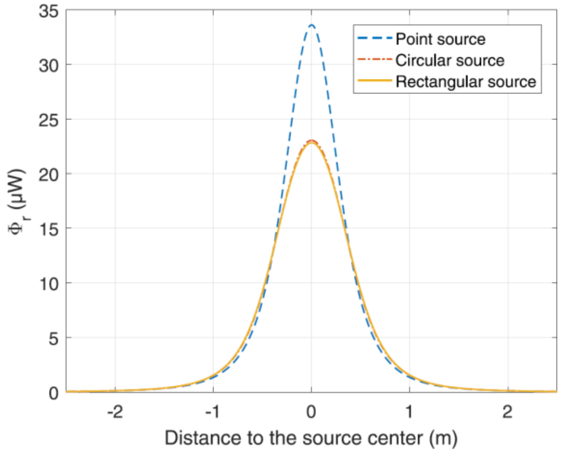
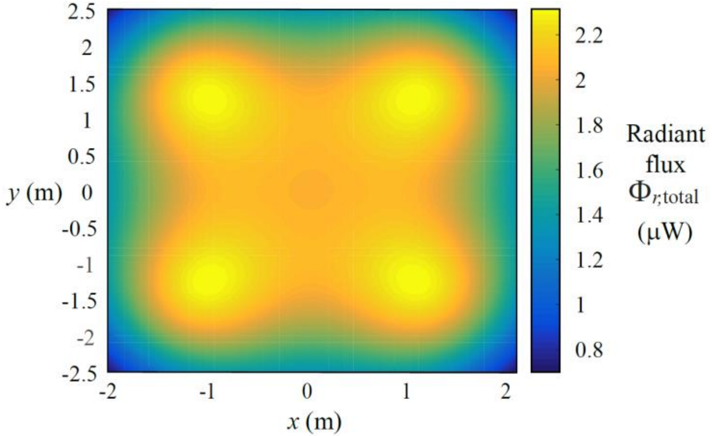
VLC Receiver Proposed

Preliminary Link Budget Evaluation

- State-of-the art link budget model assumes the light sources are point sources.
- Spots, light panels etc. ≠ point sources.
- **Consequence:** A link budget model with extended light sources has been proposed in [1].



(a) z = -0.5 m



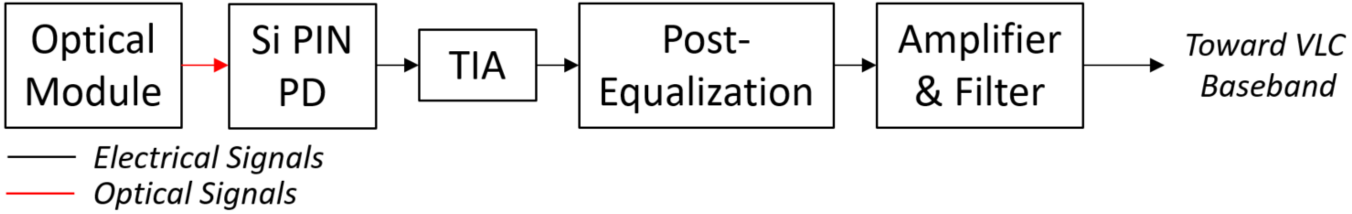
(a) Total radiant flux distribution $\Phi_{r;\text{total}}$ (μW).

[1] C. Valencia-Estrada, B. Béchadergue, and J. Garcia-Marquez, "Full Field Radiant Flux Distribution of Multiple Tilted Flat Lambertian Light Sources", IEEE Open Journal of the Communications Society, vol. 1, pp. 927-942, 2020.

VLC Receiver Proposed

Receiver Architecture

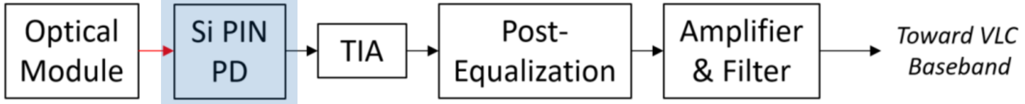
- **Architecture**:

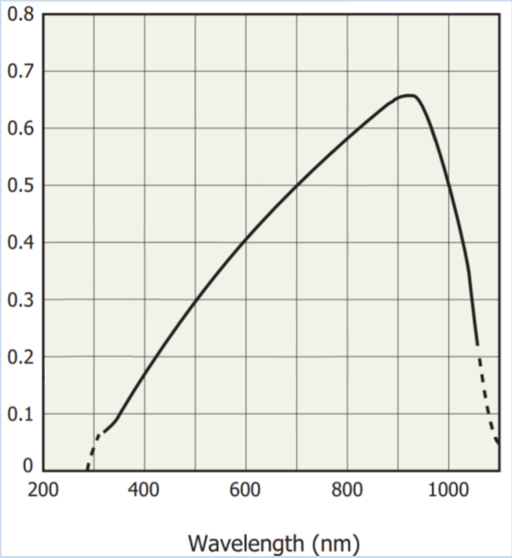


- **Components Role**:
  - Optical module: Increase the VLC light flux collected and concentrated on the PD.
  - Si PIN PD: Convert light flux into a photocurrent.
  - Transimpedance amplifier (TIA): Convert the photocurrent into an amplified voltage signal.
  - Post-Equalization: Extends the receiver bandwidth.
  - Amplifier & Filter: Signal processing for adaptation to the VLC baseband input.

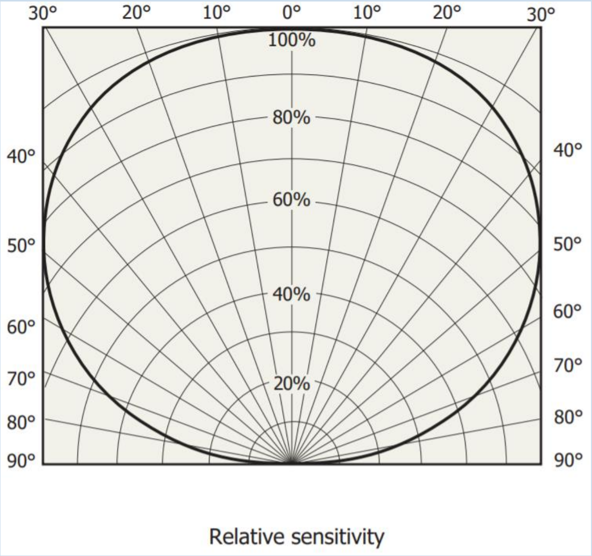
VLC Receiver Proposed

Photodiode Choice





Parameter	Value
Sensitive area	26.4 mm²
Photosensitivity	0.18 A/W @400 nm 0.59 A/W @ 800 nm
Capacitance	40 pF
Cut-off frequency	50 MHz
Field-of-view	120°



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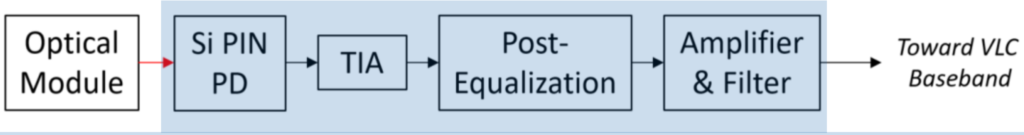
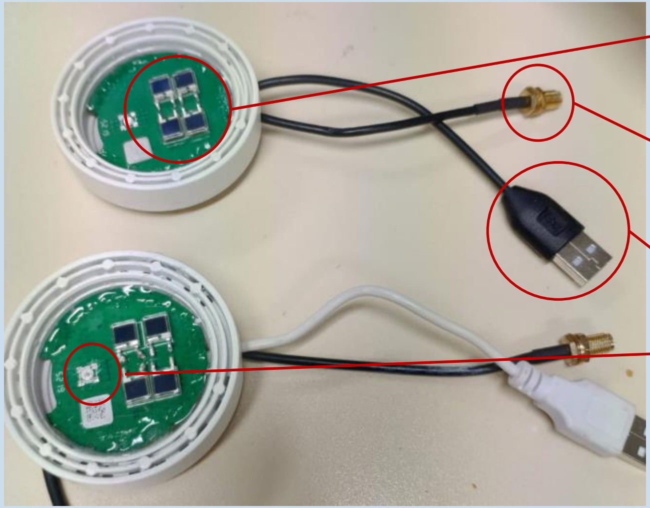
VLC Receiver Proposed

Resulting VLC Receiver





- 4 photodiodes to increase sensitive area in a circuit designed to avoid bandwidth reduction
- SMA interface for connection with the baseband
- USB interface for power supply
- Infrared LED integrated to add a transmitter for test purpose
- Dimensions: 48 mm diameter, 6 mm thickness

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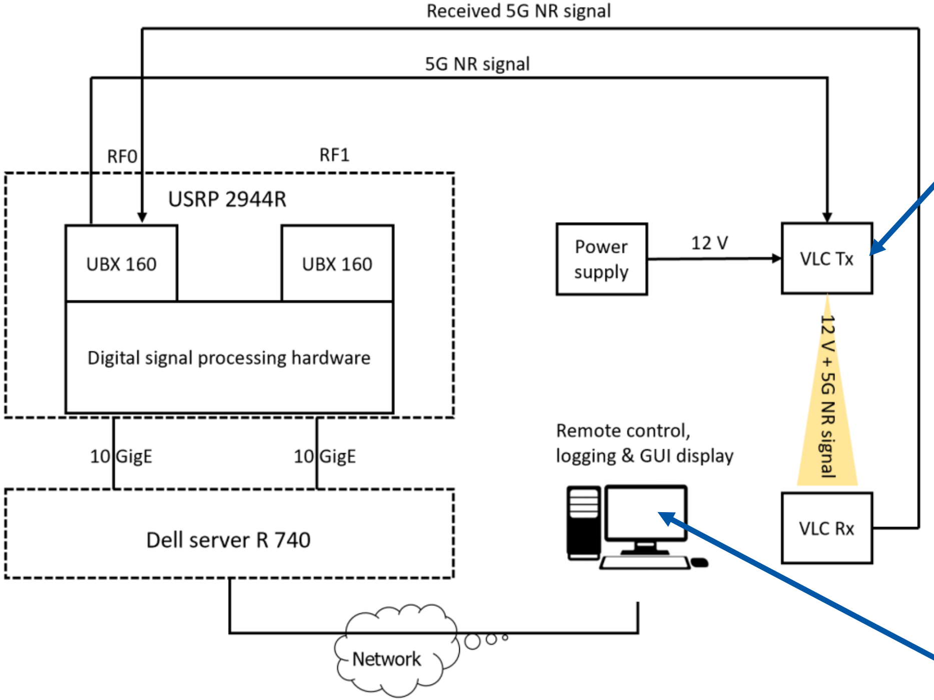
Performance Evaluation

Reference Receiver Tests: Set-Up



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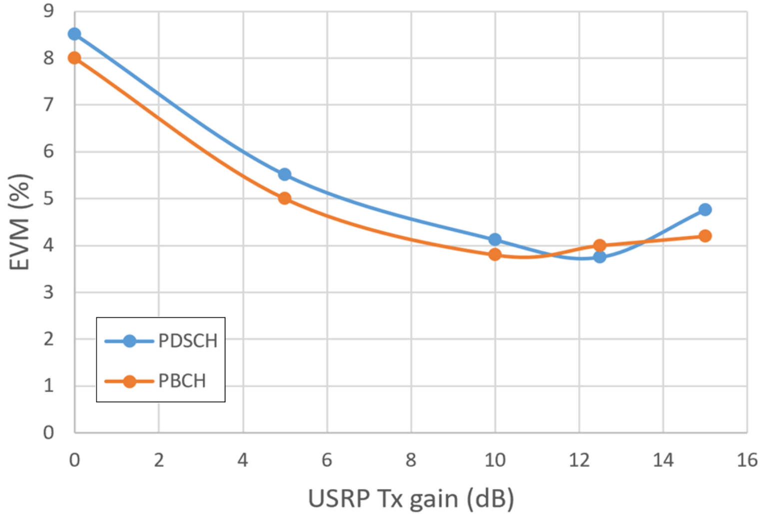
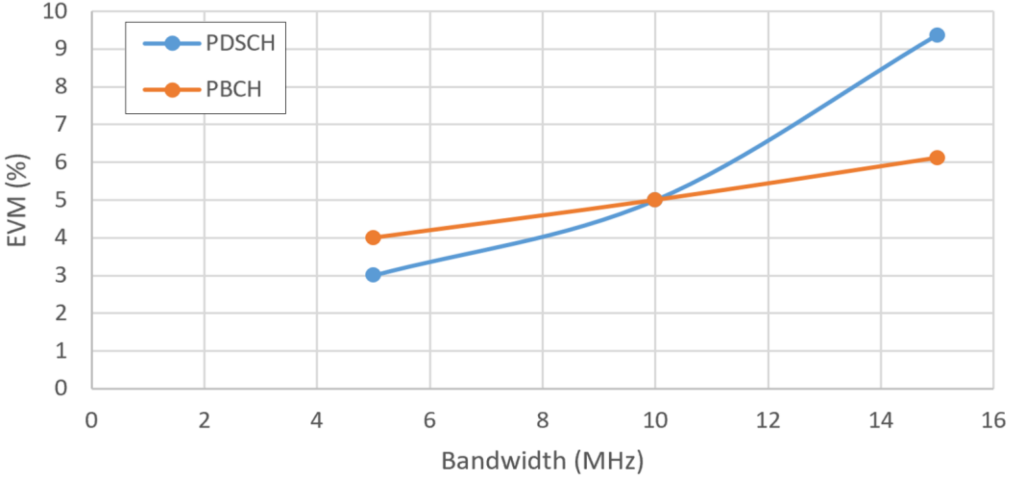
Performance Evaluation

Reference Receiver Tests: System Calibration

EVM of PDSCH/PBCH with Different USRP Transmitting Gains



EVM of PDSCH and PBCH with Different Bandwidths



- Best EVM: 3.75% with -3 dBm Tx power (☑ 64QAM)

- Best EVM: 3.01% at 5MHz bandwidth (☑ 256QAM).
- Worst EVM: 9.37 % at 15MHz (☑ 64QAM).

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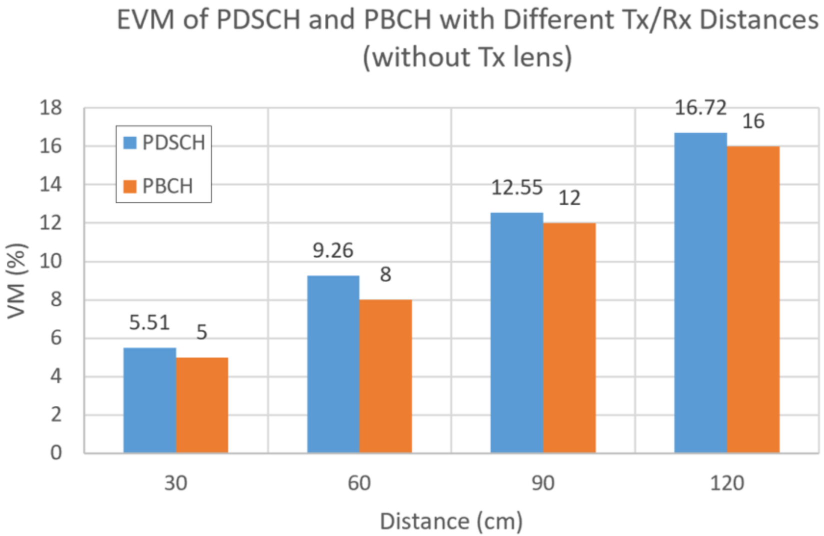
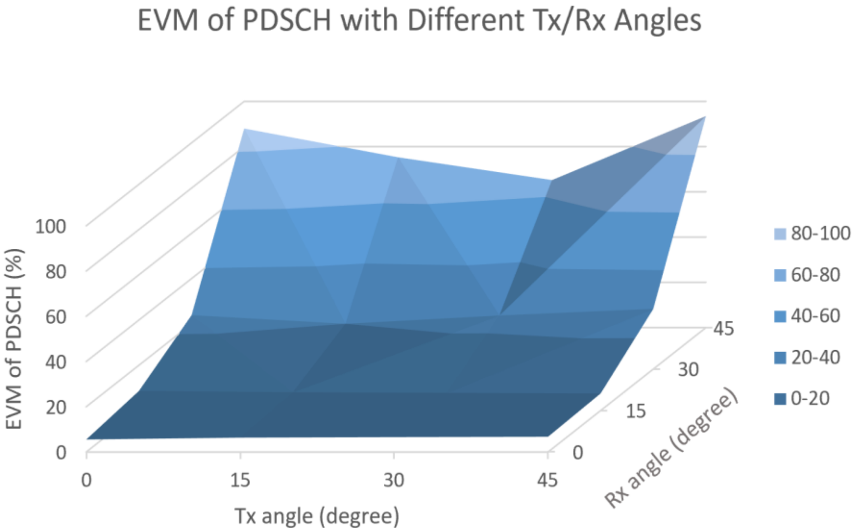
Performance Evaluation

Reference Receiver Tests: EVM and Data Rate





- Maximum distance: 180 cm with 5.82% EVM of PDSCH (☑ 64QAM).
- Maximum throughput: 31.44 Mbps (with 64QAM and 772/1024 code rate)

- Best EVM: Obtained with aligned Tx/Rx (0°).
- With Tx angle = 0° / Rx angle = 45° → EVM of 6.72% (☑ 64QAM).

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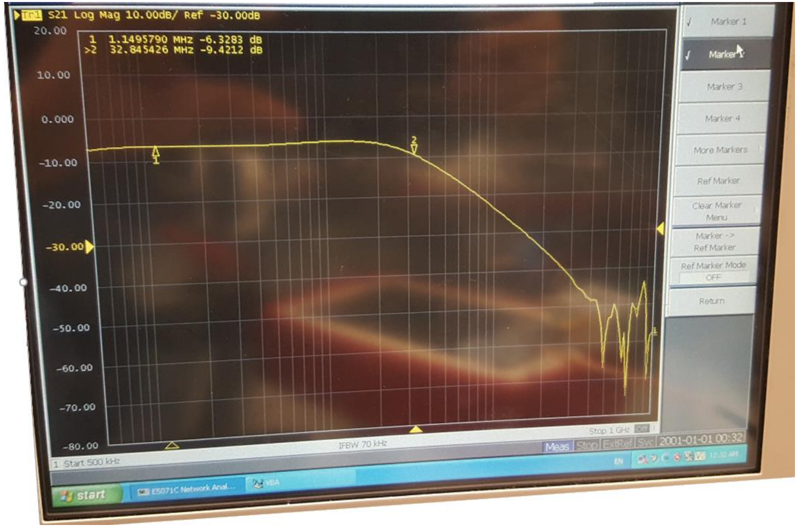
Performance Evaluation

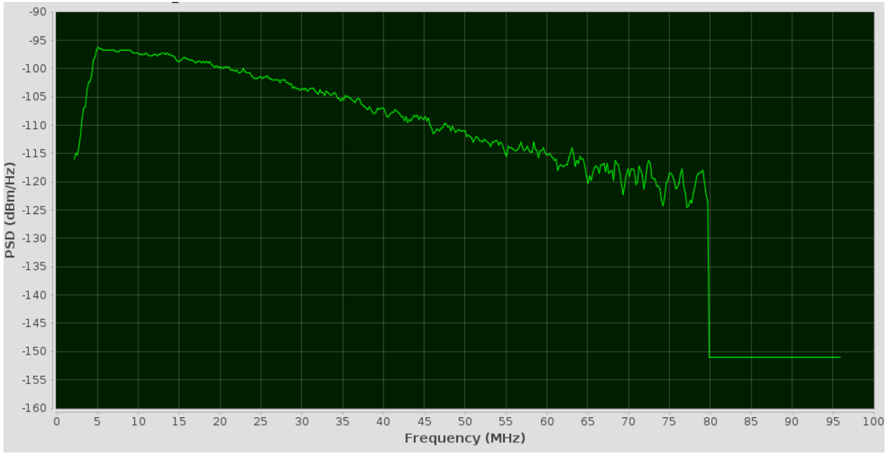
Custom Receiver Tests: Bandwidth

PIN PD-Based Receiver Bandwidth



- 3dB bandwidth of 38 MHz
- 0.5dB gain variation over the interval 10 – 20 MHz

Infrared Test LED-Based Transmitter Bandwidth



- 3dB bandwidth of 20 MHz
- 1.5 dB gain variation over the interval 10 – 20 MHz

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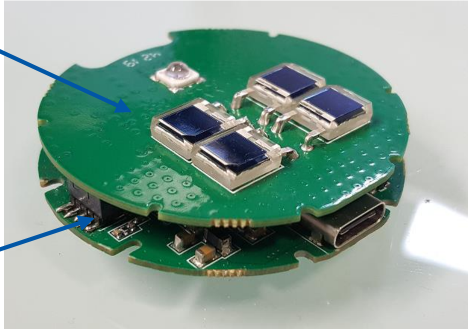
Performance Evaluation

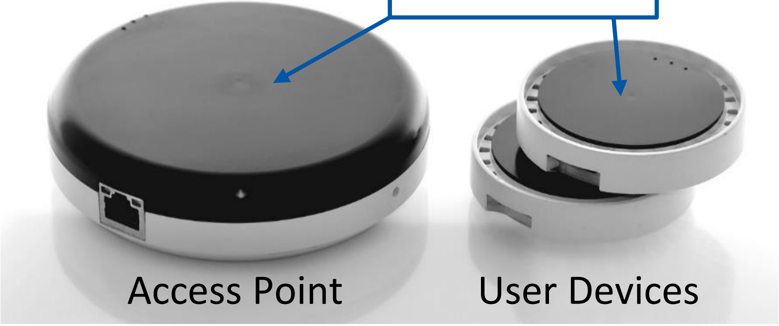
Custom Receiver Tests: Set-Up (1/2)

- **Goal:** Evaluate the best performance achievable with the designed receiver.
- **Problems:**
  - No white light source available with enough bandwidth,
  - No 5G-NR MAC and PHY available at Oledcomm.
- **Solution:** Use of a custom-made ITU-T G.vlc baseband for light communication with the infrared test LED embedded on the receiver boards.

Front-end board

Baseband board





Infrared filters

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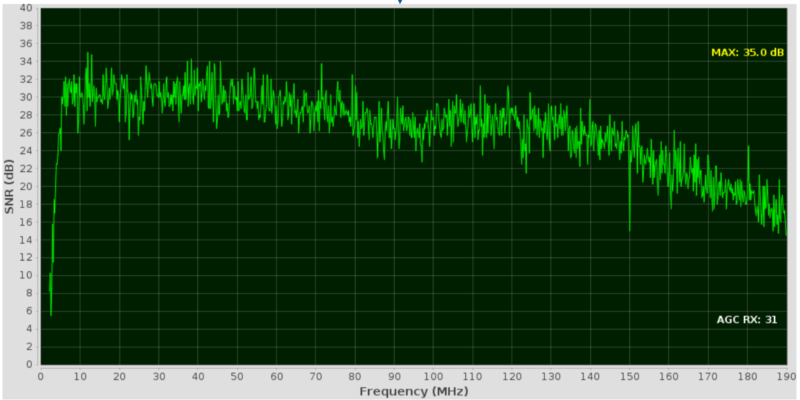
Performance Evaluation

Custom Receiver Tests: Set-Up (2/2)

Infrared access point (with photodiodes to receive uplink data)

LC receiver (with infrared LED enabled to send uplink data)

Computer for performance monitoring (data rate, noise, SNR, PSD…)



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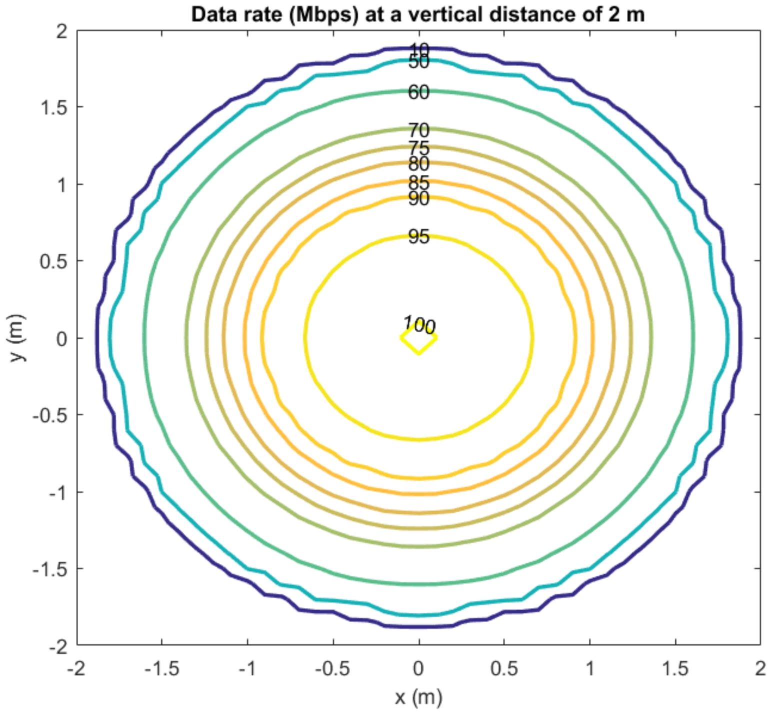
Performance Evaluation

Custom Receiver Tests: Data Rate vs Coverage

- Data rate R_b:
  - Maximum of 100 Mbps
  - Minimum of 20 Mbps
- Coverage area:
  - Full coverage of 11 m²,
  - Coverage with R_b > 50 Mbps of 10 m²,
  - Coverage with R_b > 75 Mbps of 5 m²,
  - Coverage with R_b > 90 Mbps of 2.5 m².



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Conclusions

Summary and Future Works

- **In summary:**
  - ✓ Design of a cheap and compact photoreceiver module adapted to light communication over channels of at least 20 MHz bandwidth,
  - ✓ Data rate of up to 100 Mbps (even 1 Gbps with a 150 MHz bandwidth receiver),
  - ✓ Coverage of 11 m^2 (10 m^2 more than 50 Mbps),
- **Future works**:
  - ✓ Tests of this receiver in the IoRL system with white LED transmitter,
  - ✓ Tests of this receiver in the IoRL system with infrared transmitter.

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Acknowledgment and Disclaimer

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Thank you for your attention

Contacts:

bastien.bechadergue@oledcomm.net
IoRL-contact@5g-ppp.eu

Project Website:

https://iorl.5g-ppp.eu/

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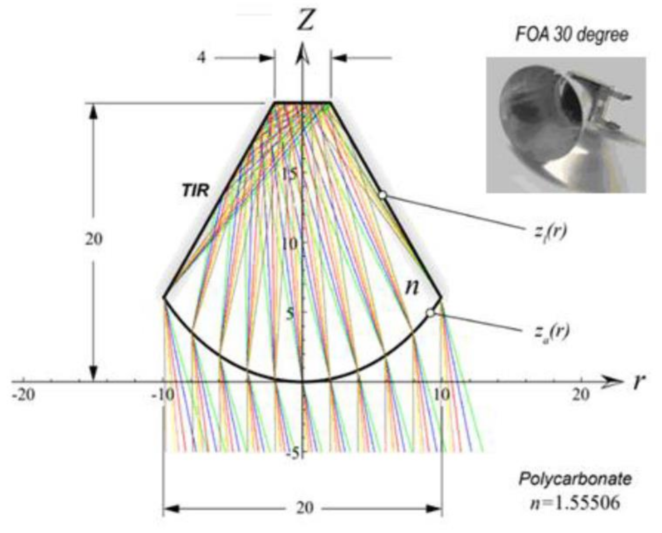
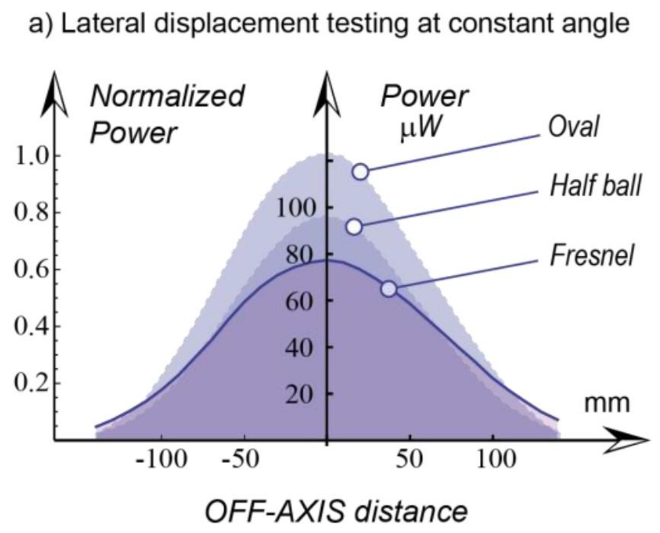
VLC Receiver Proposed

Optical Module [2]

Optical Module → Si PIN PD → TIA → Post-Equalization → Amplifier & Filter → *Toward VLC Baseband*





[2] J. C. Valencia-Estrada, J. Garcia-Marquez, X. Zhang, and L. Shi, "Freeform compound concentrators for optical wireless communications", in 2019 Global LiFi Congress (GLC), June 2019.

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