Steered Narrow Optical Beams for Next Generation Indoor Wireless Communication

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EINDHOVEN UNIVERSITY OF TECHNOLOGY

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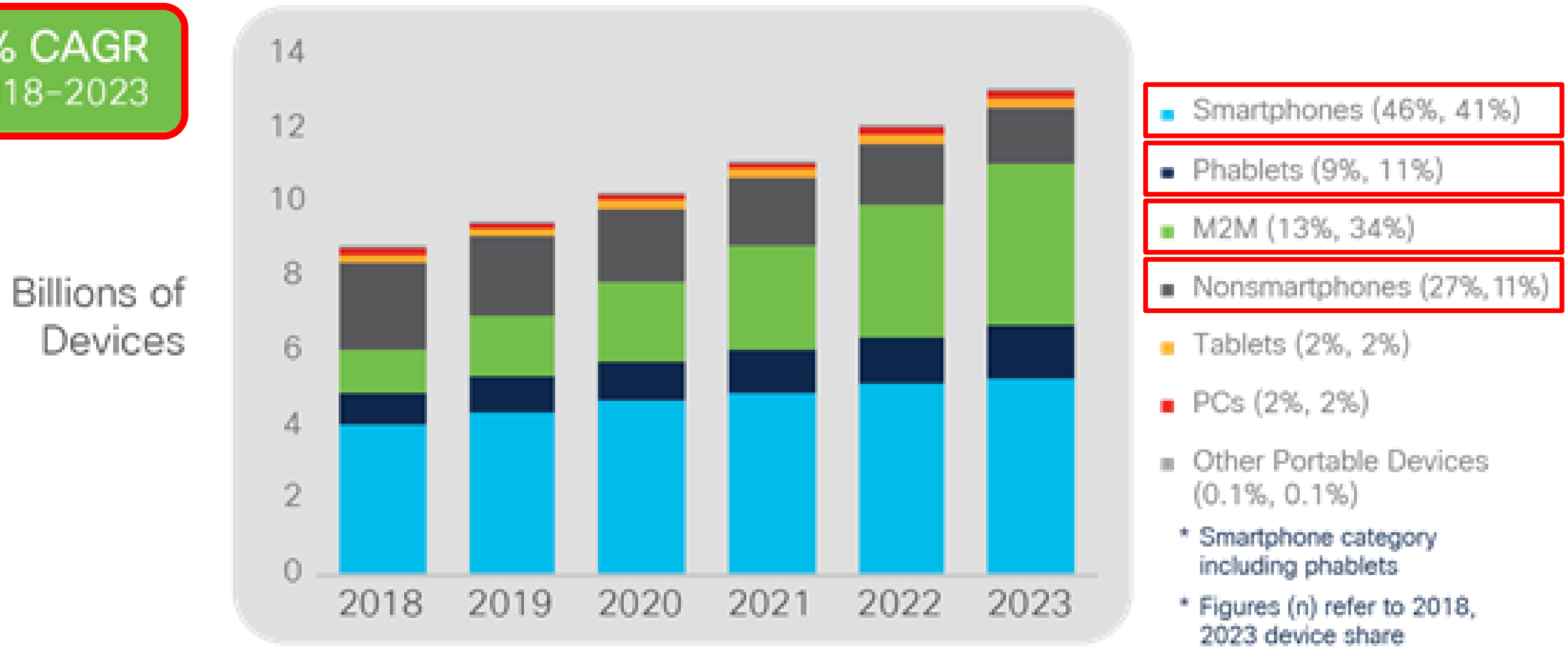
Materials · Devices · Systems

Outline

- Motivation
- Optical wireless communication system techniques for indoors
- Beam-steered optical wireless communication
- Challenges and solutions in optical-wireless communication
- Optical-wireless communication demonstrator
- Application areas
- Conclusion

Global Mobile Device and Connection Growth

8% CAGR
2018–2023



Source: Cisco Annual Internet Report, 2018–2023

- Radio spectrum is getting seriously congested → interference among devices
- More wireless traffic is coming from <u>indoor</u> devices than from <u>outdoor</u> ones

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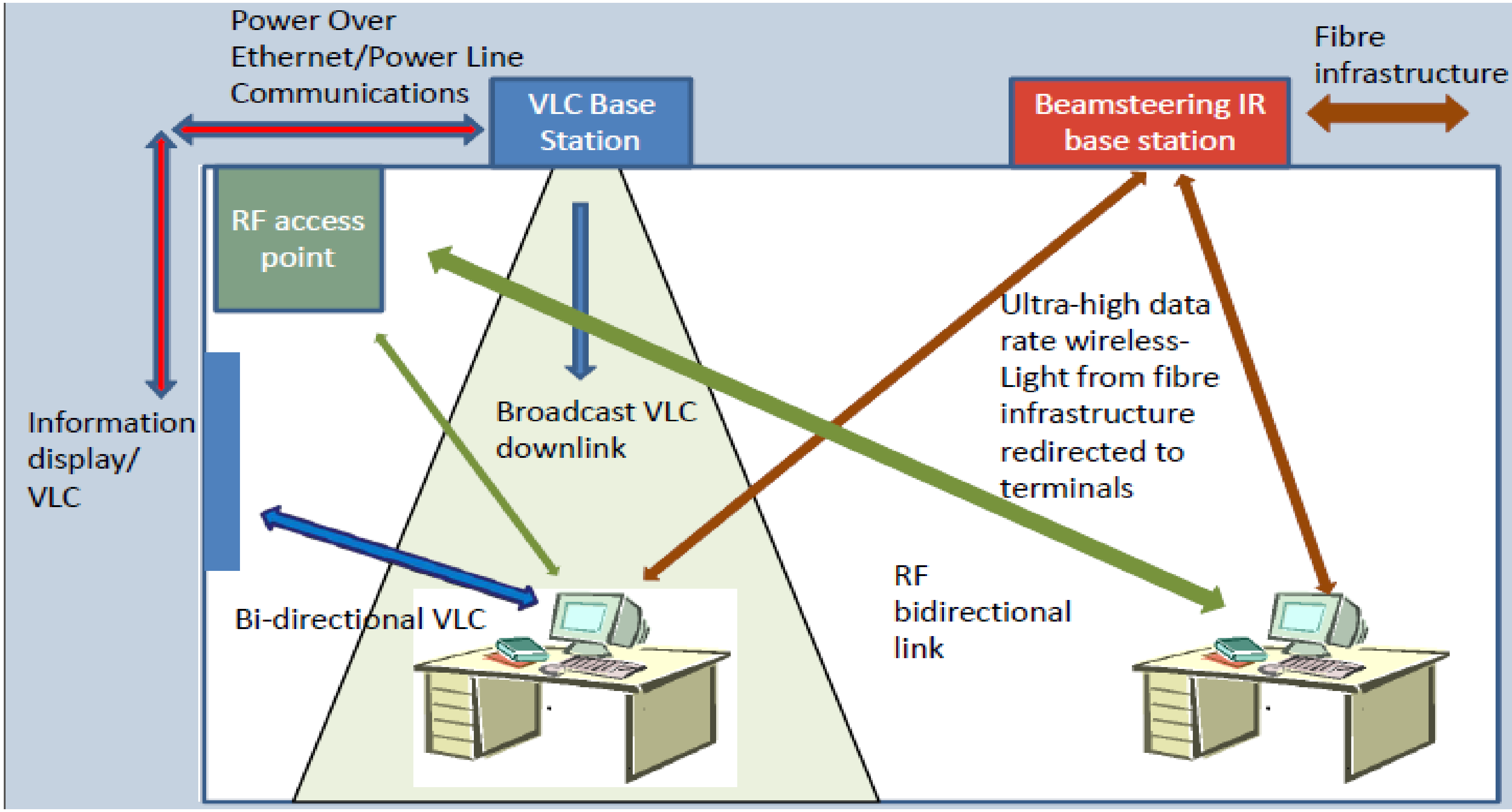
Optical Wireless Communication (OWC) – basic options



- **Visible Light Communication** with wide-coverage beams (<1Gbit/s, <u>shared</u>)
- **Beam-steered IR communication** (>10Gbit/s, <u>unshared</u>)
- **User environment** $\rightarrow$ true mass deployment, requires scalable manufacturing, power efficiency, cost-effectiveness $\rightarrow$ **photonic integration of OWC functions**

[Dominic O'Brien, IPS Summer Topicals 2016]

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USP-s of Indoor Beam-steered OWC vs. WiFi, LiFi

WiFi, LiFi

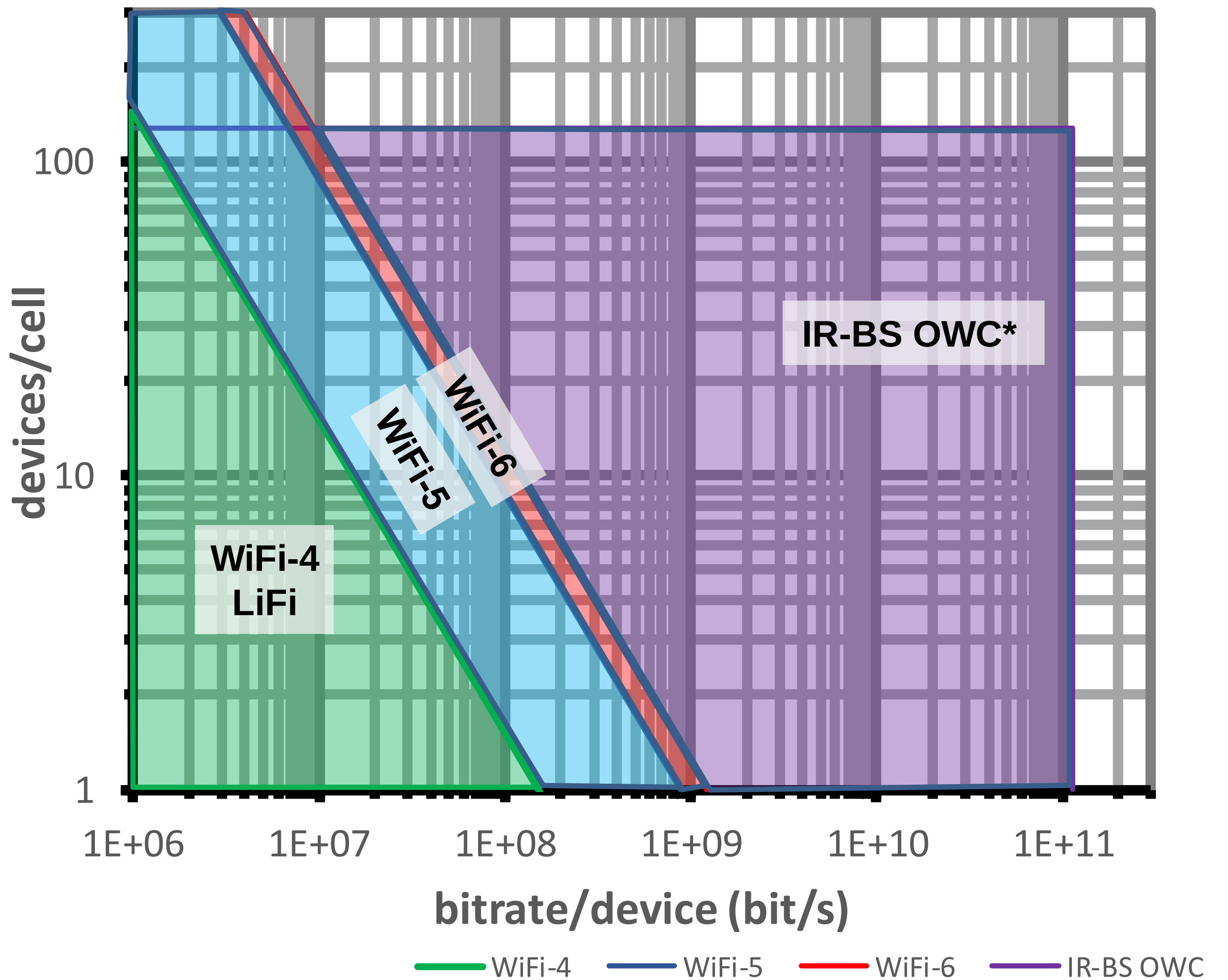
<u>Shared</u> capacity ⇨

- bitrate × no. devices restricted
- privacy issues
- EMI sensitive (WiFi)

Beam-steered OWC

<u>No</u> capacity sharing ⇨

- much higher user density
- much higher bitrate/device
- personalized, enhanced privacy
- no EMI disturbances
- high energy efficiency, signal only where and when needed



* a.k.a. 'LiFi 2.0'

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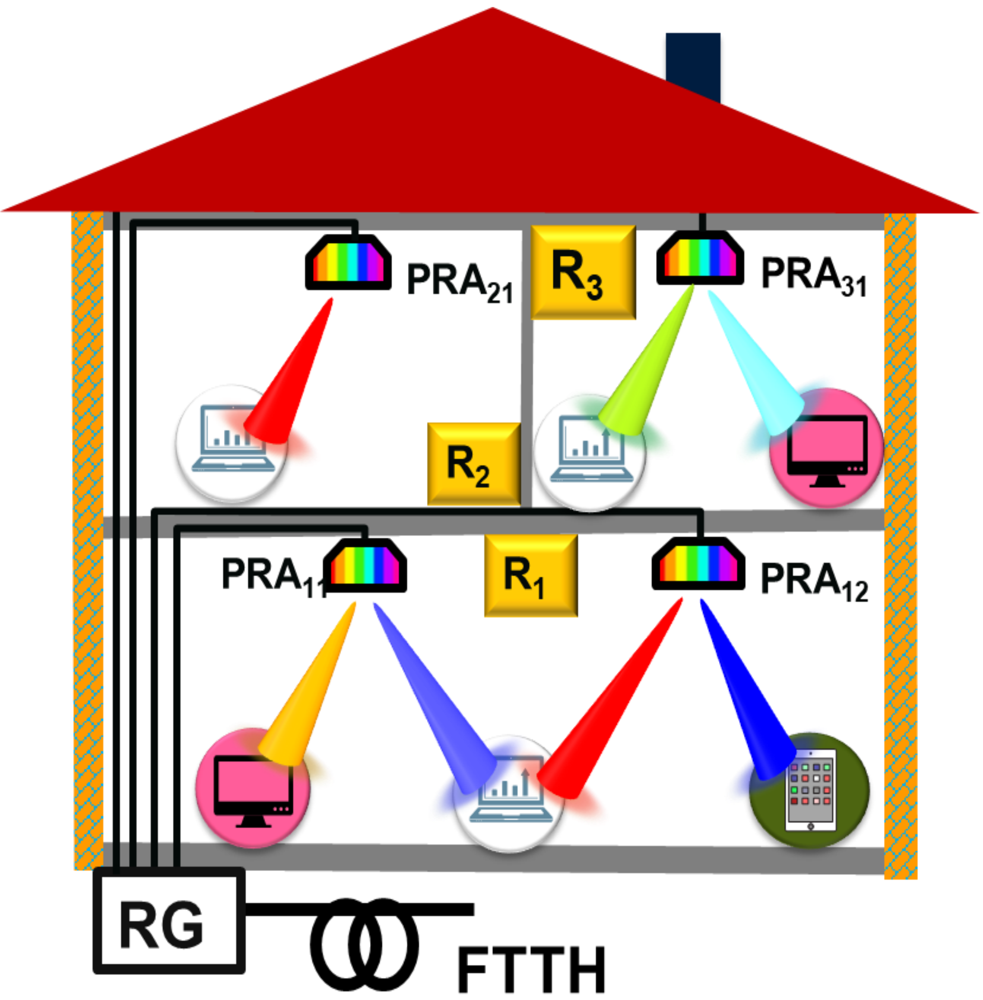
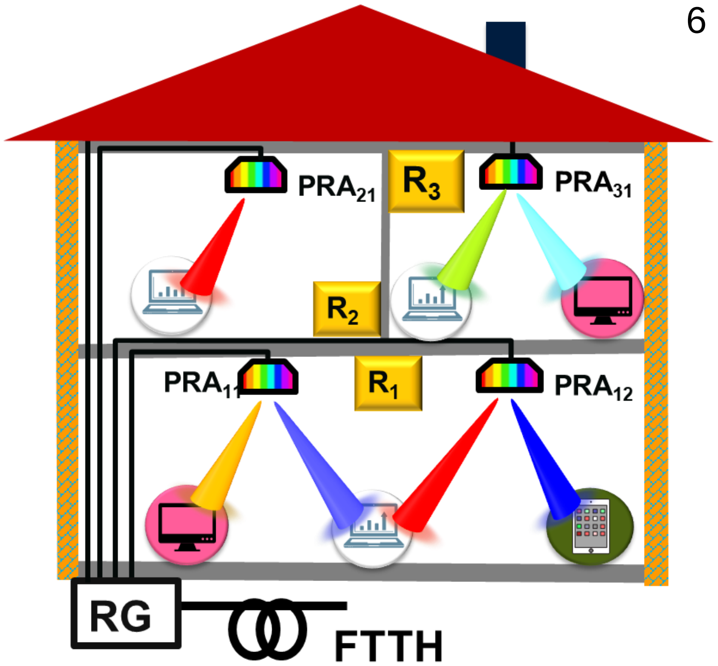
Challenges with Indoor Beam-steered OWC



1. → OWC Transmitter
2. → OWC Receiver
3. → User localization
4. → Bidirectionality

2D Beam Steering for indoors



Requirements:

- **Simultaneously steering**
- **2D Steering**
- **Large channel BW**
- **Fast steering speed**
- **Large coverage area (FoR)**
- **Compact & low power consumption**

Solutions reported:

- **Spatial Light Modulator**, 512×512 pixels, 256 phase levels[1]
  - Max. steering angle ≈ 3°, with angle magnifier: ≈ 60°
  - 3λ × 37.4Gbit/s = 112Gbit/s
- **MEMS mirror**[2]
  - Steering range >20°
  - Free-space link 2m, max. coverage area 113cm,10Gbit/s per beam
- **Crossed gratings**[3]
  - Fully **passive** device, wavelength based steering
  - Angular tuning over 5.6°×12.7°, Multiple beam capable

1. [A. Gomez et al., PTL Feb. 2014 (Oxford Univ.)]
2. [Ke Wang et al., OFC2015 (Univ. Melbourne)]
3. [Koonen et al, US Pat. 9246589, d.d. Jan. 20, 2012]

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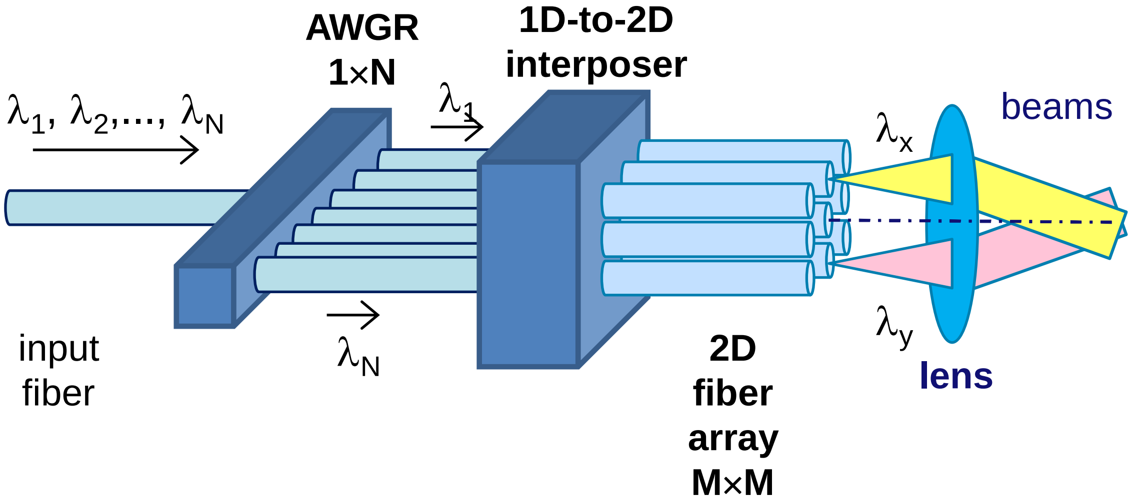
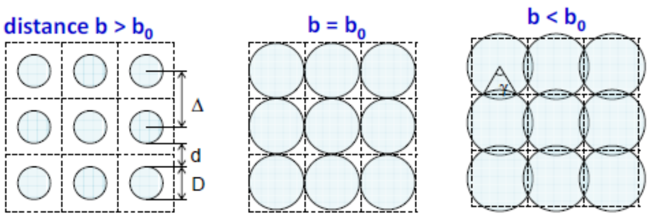
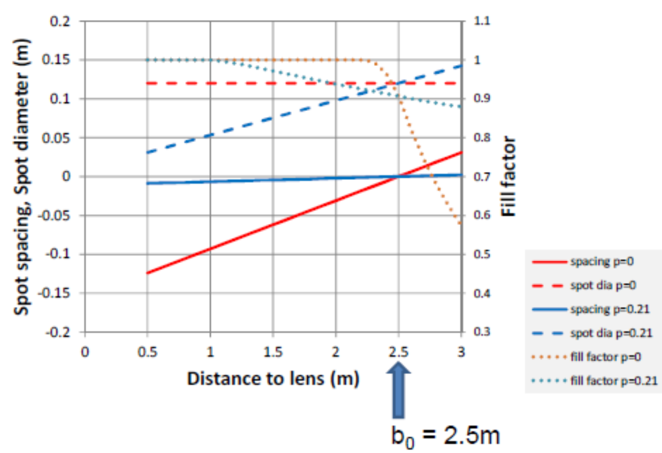
2D beam Steering with High Port Count Arrayed Waveguide Grating Router



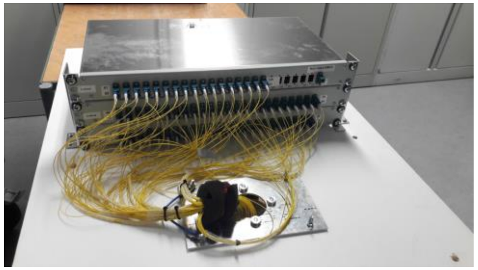




- Fully **passive** device
- Deploys **only wavelength tuning**

128 fibers array

+ f=50mm lens objective



+ (C+L$^-$) AWGR

[Koonen et al, Sum. Top. 2016, JLT Oct. 2018]

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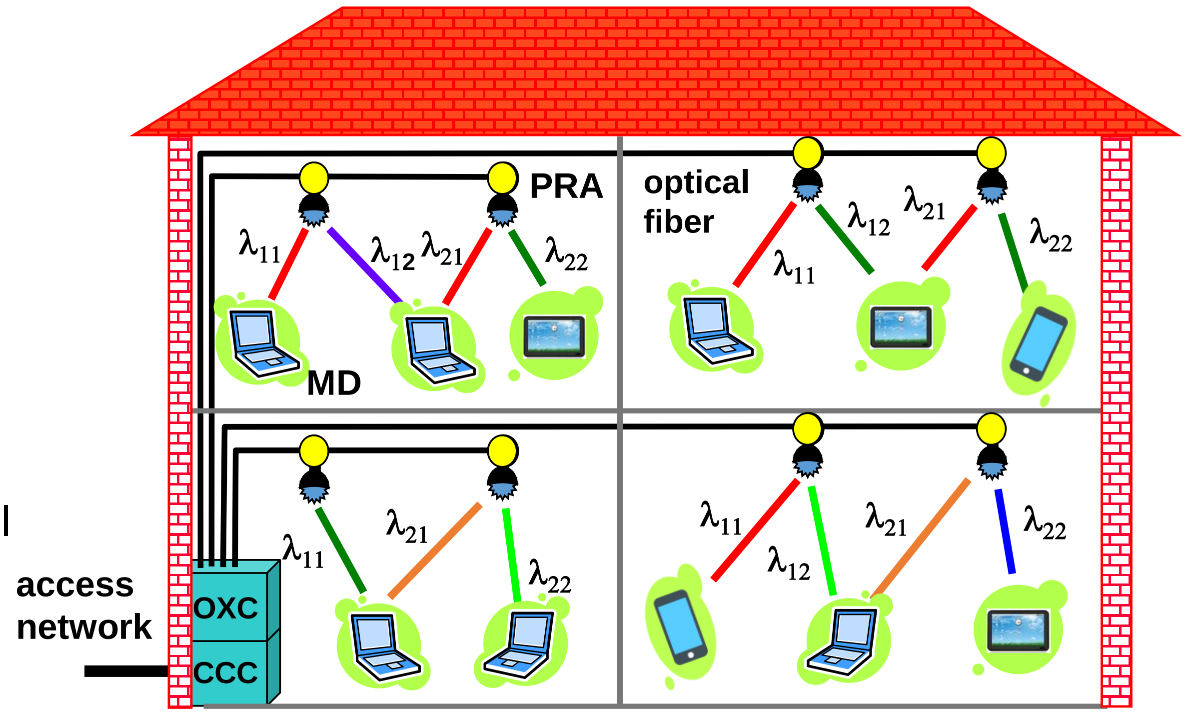
Indoor Free-space Beam-steered Optical Communication

System concept:

- **pencil beams**
  $\rightarrow$ high capacity, no sharing, long reach, private
- **IR λ>1400nm** $\rightarrow$ eye safe, P_{beam} up to 10mW
- **passive beam steerer**
  $\rightarrow$ no local powering, easily scalable
- **λ-controlled 2D steering**
  $\rightarrow$ embedded control channel
- **Scalable** to many beams, just add λ-s
- *target*:
  ≥10Gbit/s per beam



OXC = Optical Crossconnect
CCC = Central Communication Controller
MD = Mobile Device
PRA = Pencil-Radiating Antenna

[Koonen et al, MWP2014]
[Mekonnen et al., JLT May 2018, JLT Oct 2018]

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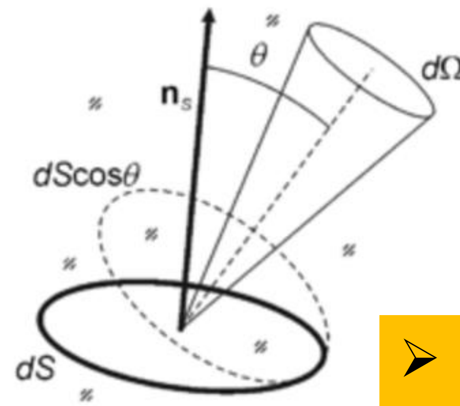
OWC Receiver Design

Law of conservation of Etendue

Requirements:
- Large bandwidth
- Large aperture
- Wide Field-of-View
- Simple
- Compact
- Low power consumption



Etendue d*G* of light crossing d*S*:

$$dG = n^2\, dS \cos\theta \;\; d\Omega$$

➢ Etendue is conserved as light travels through free space

Solutions reported:
- Non-imaging optics, such as compound parabolic concentrator
- Angular diversity receiver (multiple PD-s and TIA-s)
- PIC with large/multiple surface grating couplers + waveguide-fed UTC-PD
- Wavelength conversion in phosphorent slab waveguide or fibre
- **2D photodiode matrix + single TIA** (first reported at ECOC2020* ; with 4 quad PD-s) - PATENTED

* Koonen et al, “Novel broadband OWC receiver with large aperture and wide Field-of-View”, ECOC2020, paper Tu2G.4

[https://en.wikipedia.org/wiki/Etendue]

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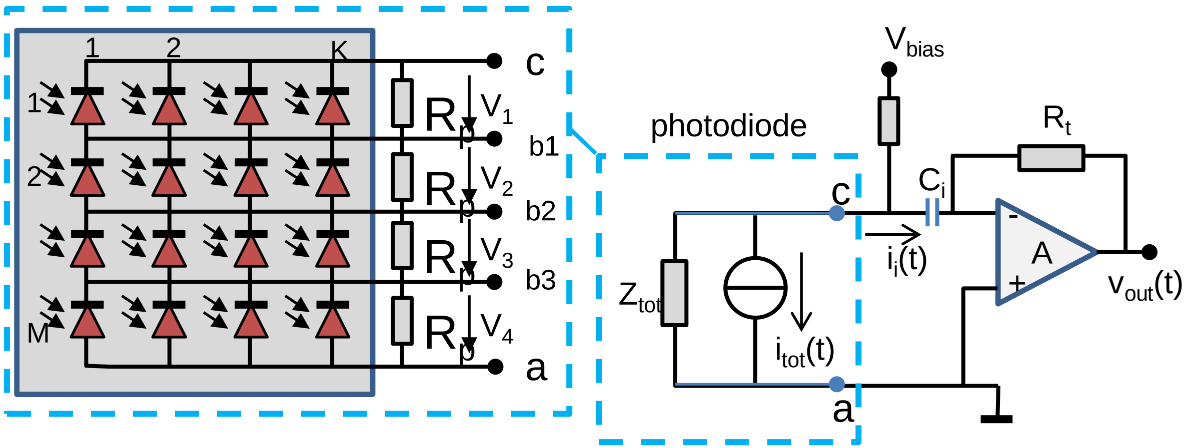
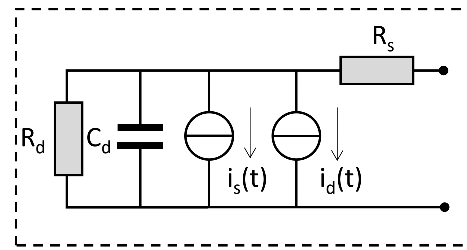
OWC Receiver with 2D Matrix of Photodiodes

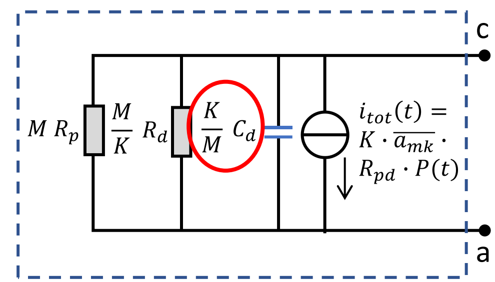
- 2D matrix of photodiodes (i.s.o. single large-area PD)
- <u>Single</u> pre-amplifier



2D matrix of photodiodes applied in transimpedance amplifier



Equivalent circuit of single photodiode



Equivalent circuit of 2D matrix of photodiodes

TIA characteristics:

$$Z_T(\omega = 0) = \left.\frac{v_{out}(t)}{i_{tot}(t)}\right|_{\omega=0} = \frac{A}{1+A} R_t$$

$$\omega_{-3dB} = \frac{1+A}{C_d \cdot R_t} \text{ if } Z_{tot} \approx \frac{1}{j\omega\, C_d}$$

$\rightarrow$ BW limit due to PD capacitance

Pat. PCT/EP2020/080594 (filed 30 Oct. 2020)

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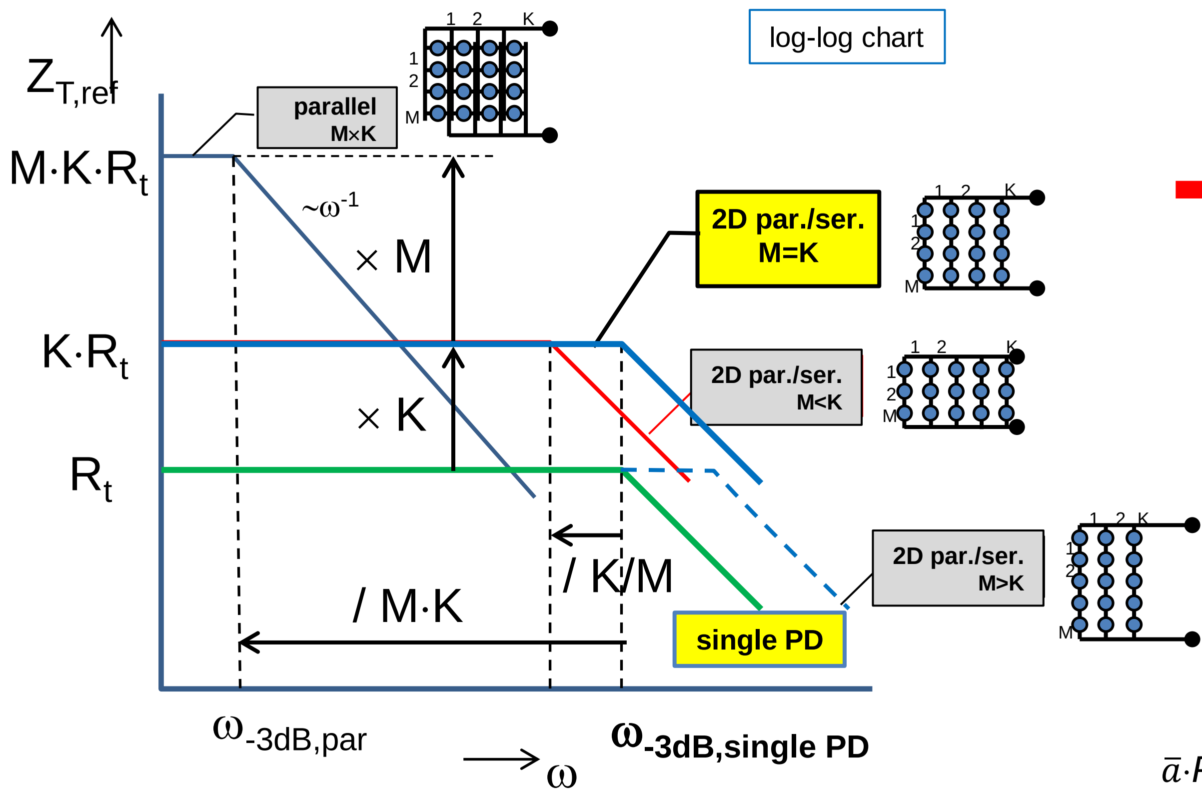
OWC Receiver - Frequency Characteristics



with a **square *M*×*M* matrix** of photodiodes in a TIA the **<u>same</u>** bandwidth is achieved as with a single photodiode, whereas **active area is *M*² times larger**, and **output signal is *M* times larger.**

$\bar{a} \cdot P(t)$: average power received per PD

$$Z_{T,ref}(\omega = 0) = \frac{v_o(t)}{\bar{a} \cdot R \cdot P(t)} \approx K \cdot \frac{A}{1+A} \cdot R_t \qquad \omega_{-3dB} \approx \frac{M}{K} \cdot \frac{1+A}{C_d \cdot R_t}$$

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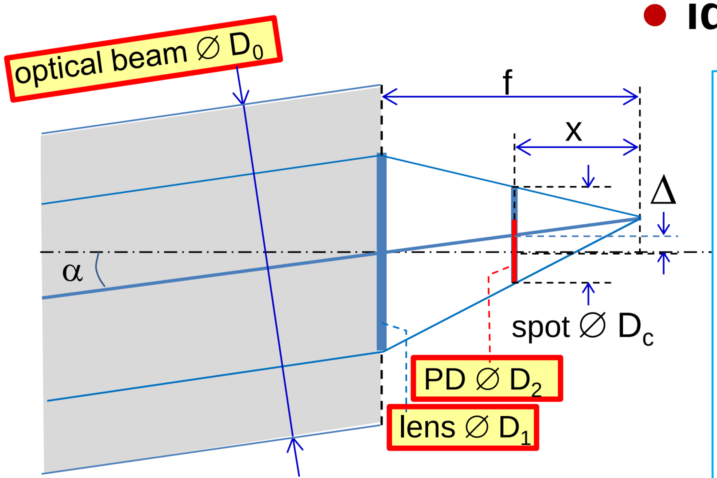
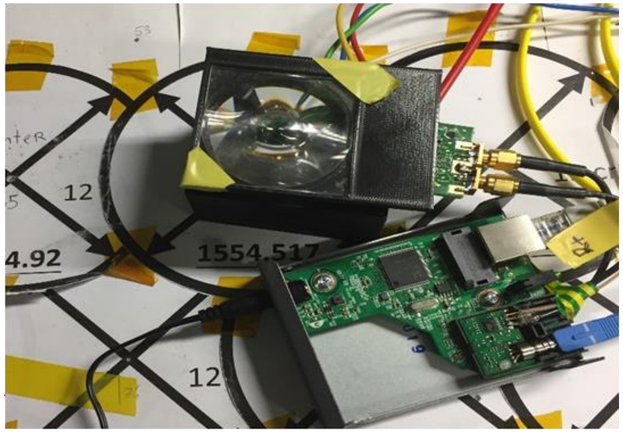
Capturing the Beam by the Photodiode Matrix





- **ideal case : uniform beam, thin aberration-free lens**

Defocusing factor p=x/f: spot size $\varnothing D_c = p\, D_1 > $ PD dia. $\varnothing D_2$

With **ideal thin lens $\varnothing D_1$ and uniform beam $\varnothing D_0$** :

- **Coupling fraction T** of beam's power into all photodiodes (matrix fill factor η)

$$T = \cos\alpha \cdot \eta \cdot \left(\frac{D_2}{p\, D_0}\right)^2 \quad \text{for } p > D_2 / D_1$$

→ **decreases if p increases**

$$T = \cos\alpha \cdot \eta \cdot \left(\frac{D_1}{D_0}\right)^2 \quad \text{for } 0 < p \le D_2 / D_1$$

- **FoV half angle α_{max} :**

$$\tan\alpha_{max} = \frac{|p \cdot D_1 - D_2|}{2\, f\,(1-p)}$$

→ **increases if p increases**

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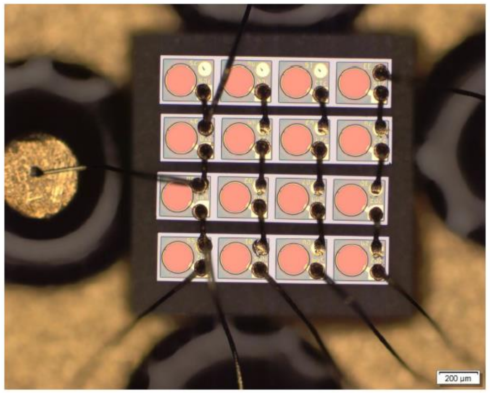
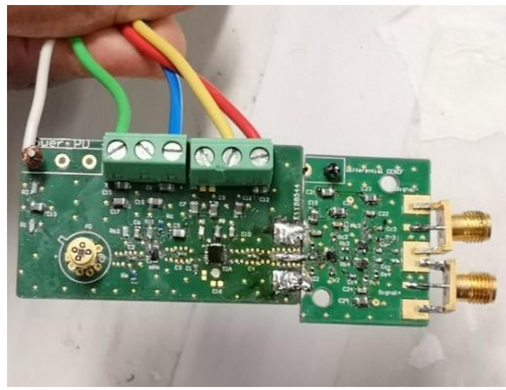
OWC Broadband Receiver Module

4×4 PD matrix
(made by Albis Optoelectronics)

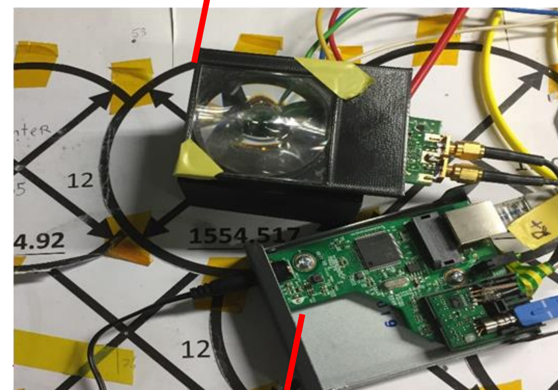


- **1.3mm x 1.3mm**
- **Fill-factor: 20%**

OWC receiver with differential outputs



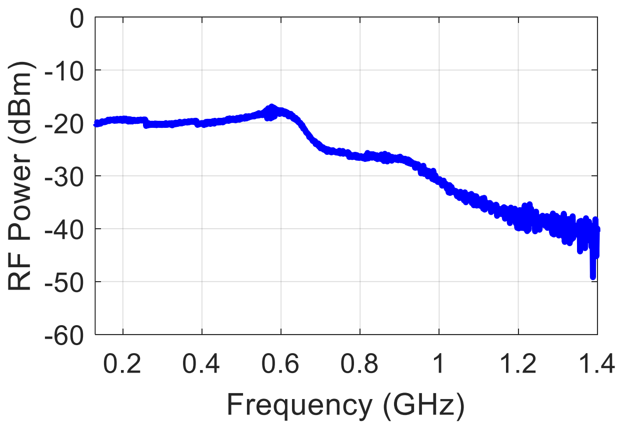
OWC receiver with ∅2” Fresnel lens



adapted media converter with RJ45 output (→ ‘OWC dongle’)

Frequency char.

BW_{-3dB} = 670MHz



Note: BW_{-3dB} mainly limited by the TIA used which has a BW_{-3dB} of 700MHz.

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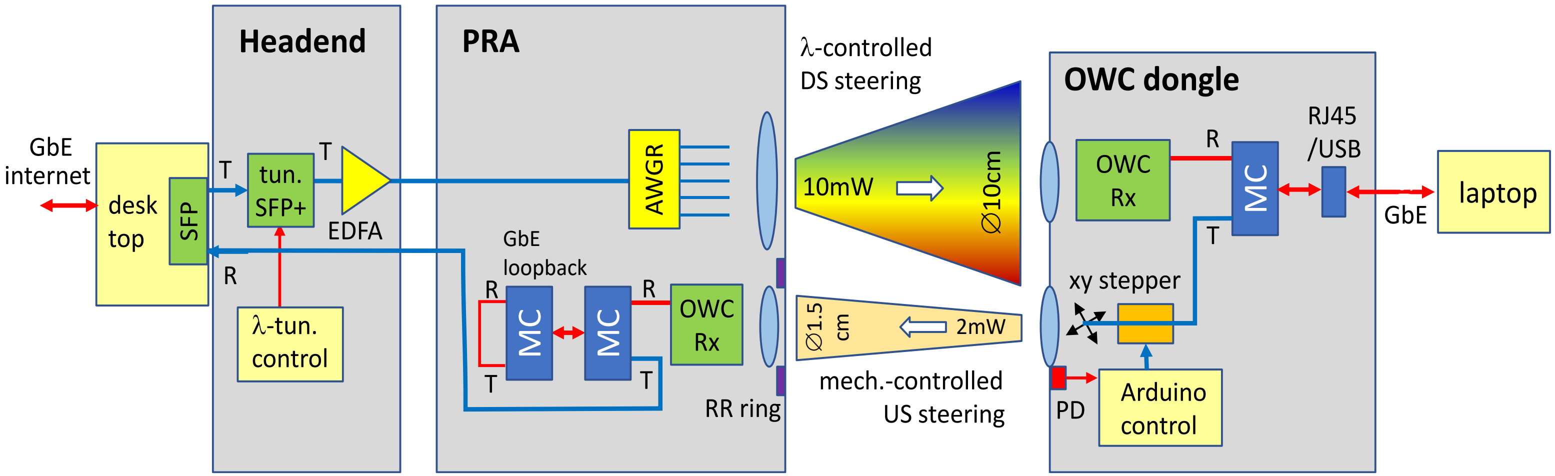
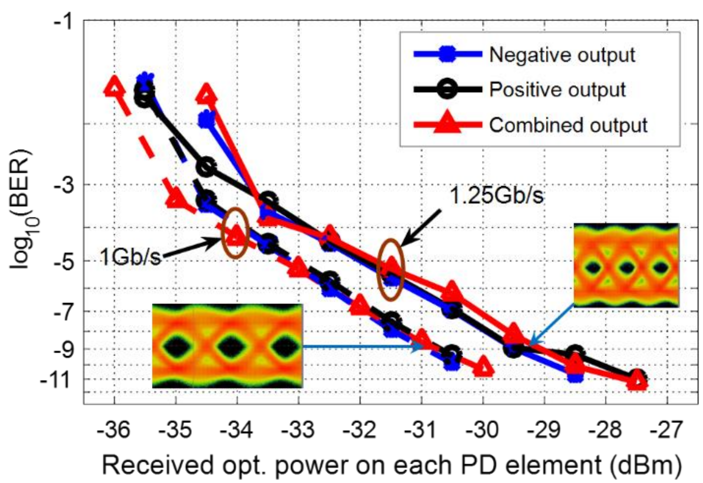
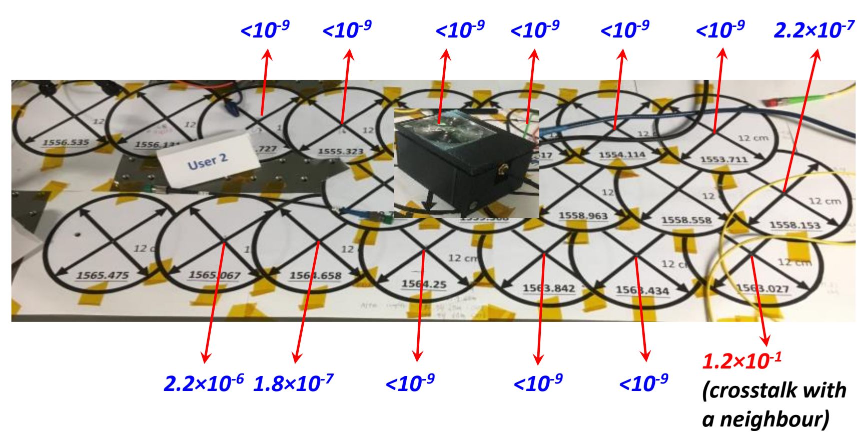
OWC Broadband Receiver Performance



Media converter (MC)



BER for both single-ended and differential receiver outputs



FoV measurements at 1Gbit/s → error-free within a half-angle FoV=10° from center cell

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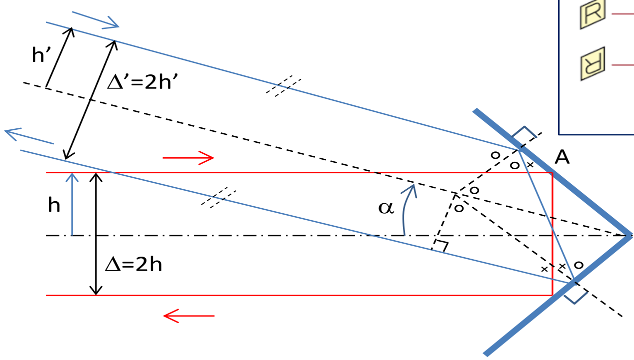
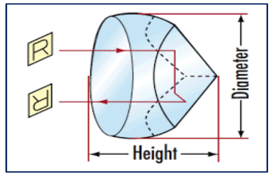
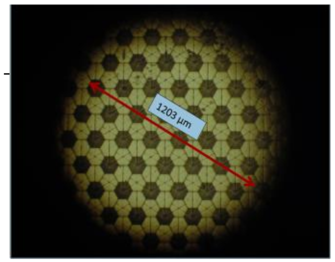
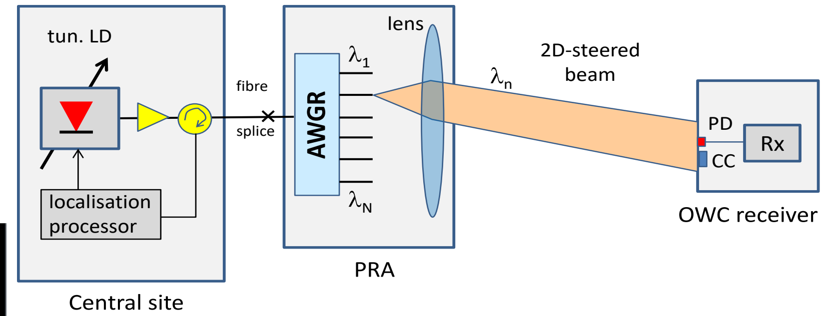
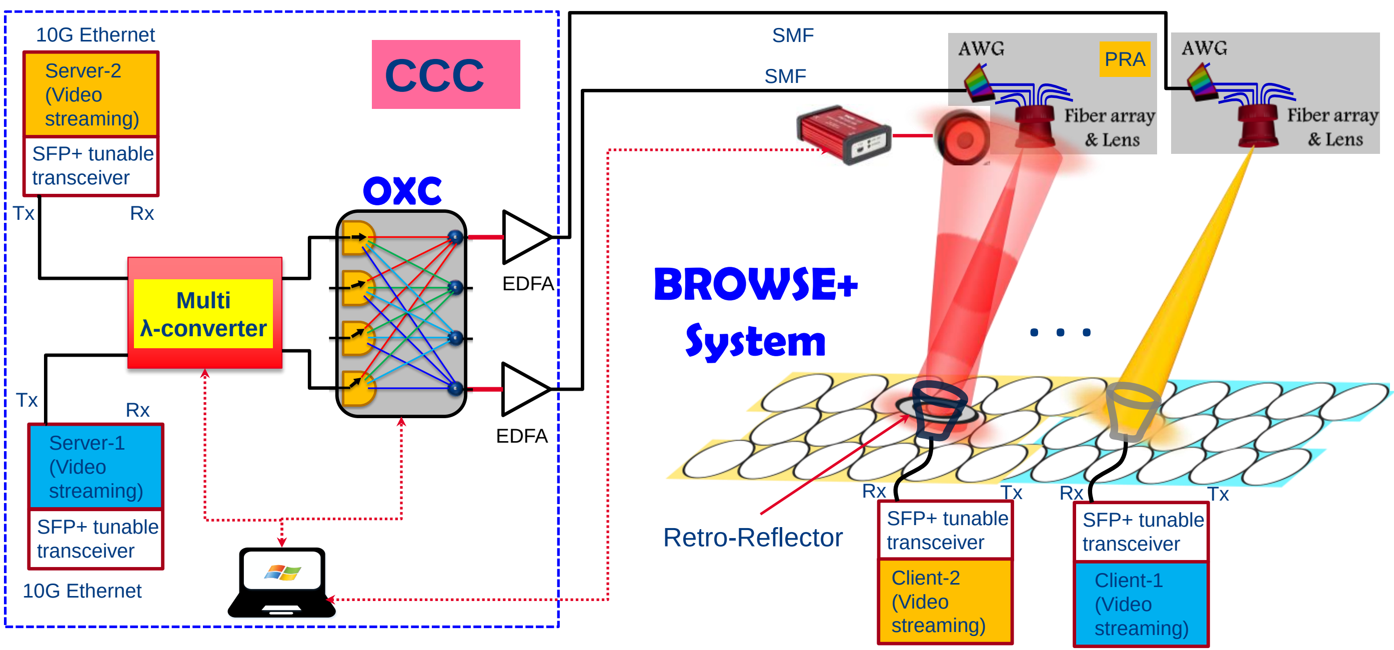
User Localization using Retro Reflector foil - Downstream

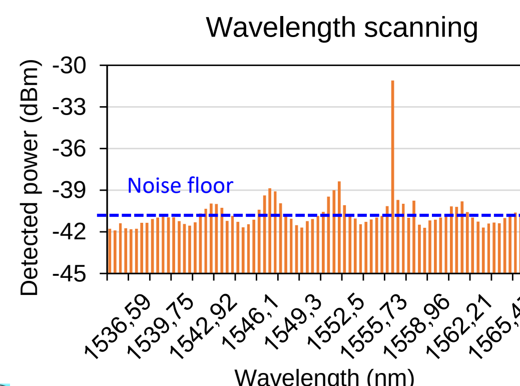












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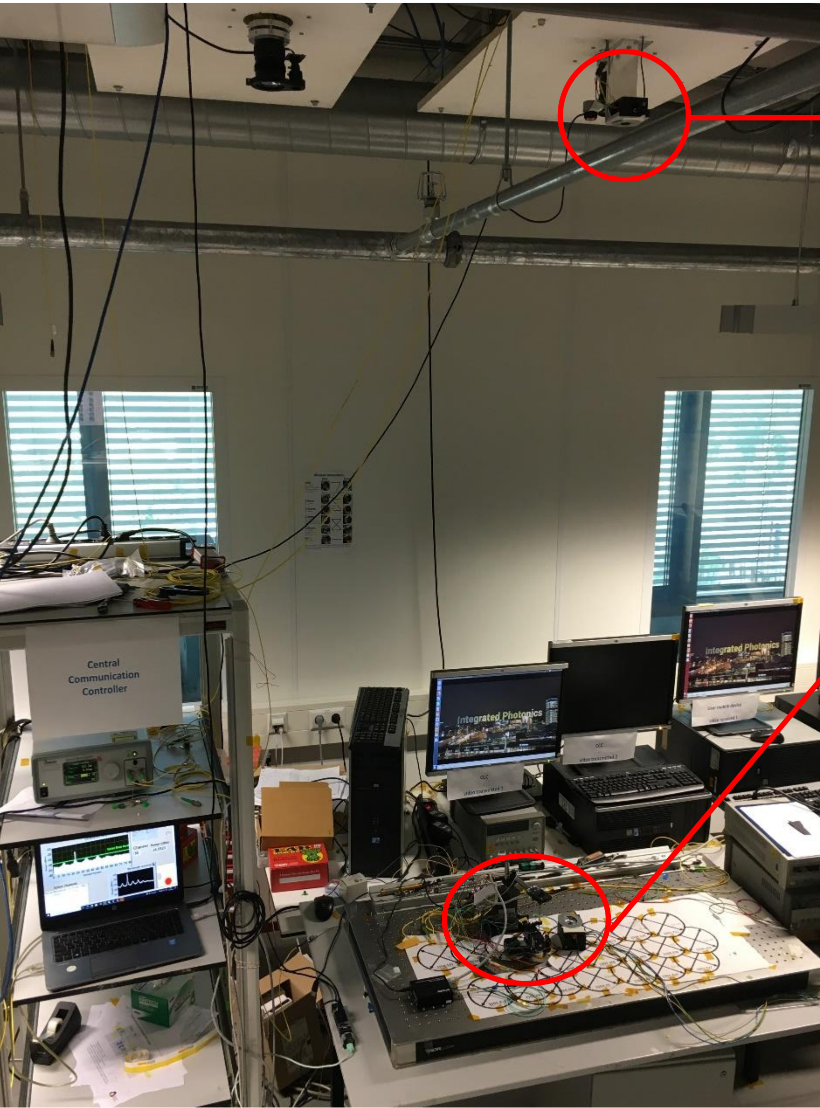
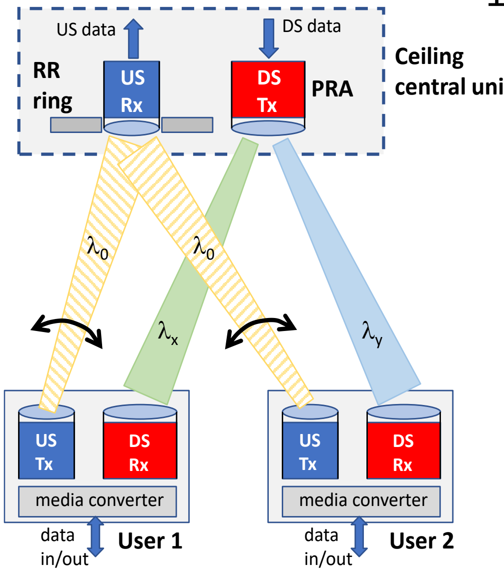
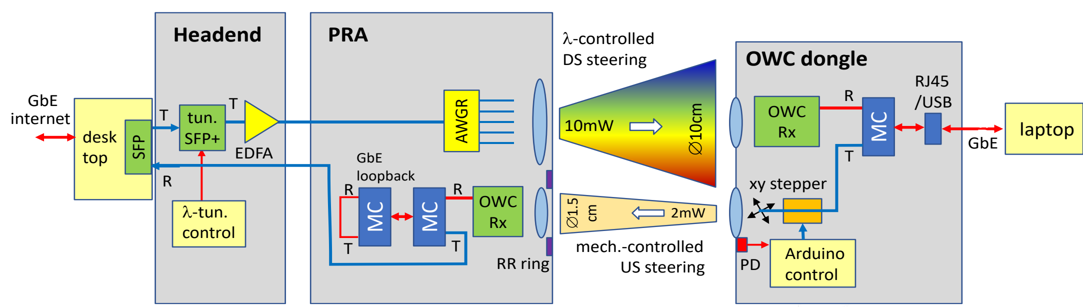
Bidirectional OWC - Upstream



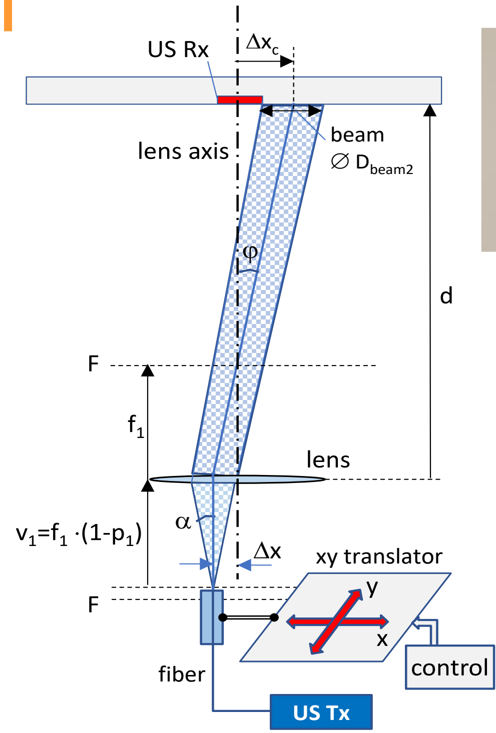
Downstream
Tx.

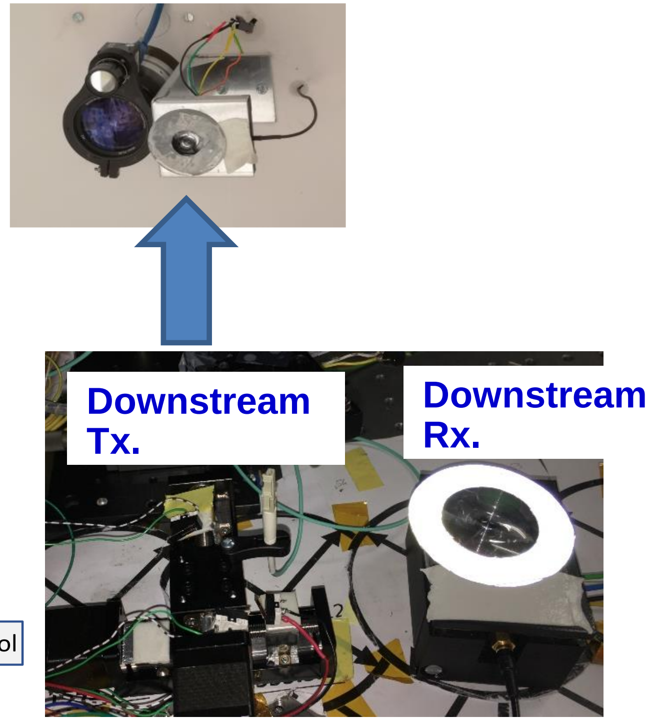


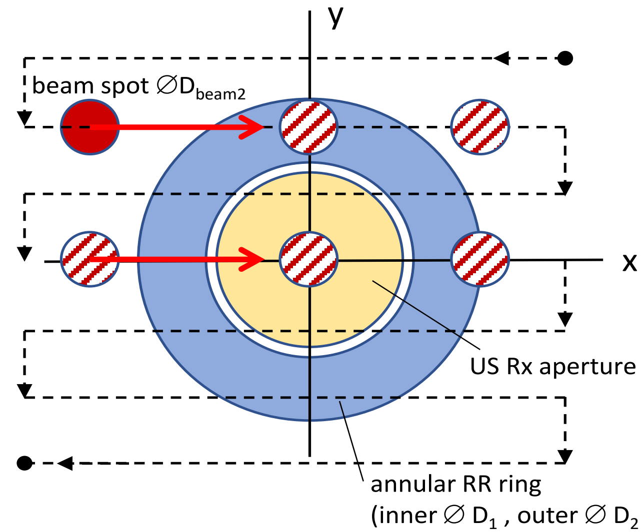
Downstream
Rx.



User Localization using Retro Reflector foil - Upstream





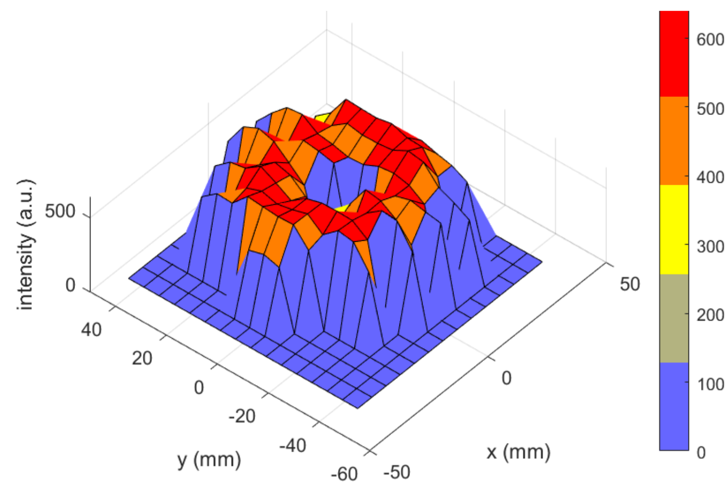


1. **Course scanning to detect the RR annular ring.**
2. **Fine scanning when detecting a reflected signal from RR. Scanning should be performed over at least the whole RR annular ring.**

   ➔ Generate measurement matrix

1. **Determine center using center of gravity algorithm.**

$$CoG = \begin{pmatrix} x_{CoG} \\ y_{CoG} \end{pmatrix} = \frac{1}{M}\sum_{i-1}^{N} m_i \begin{pmatrix} x_i \\ y_i \end{pmatrix} \text{ with } M = \sum_{i=1}^{N} m_i$$



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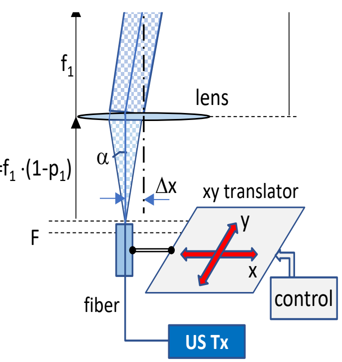
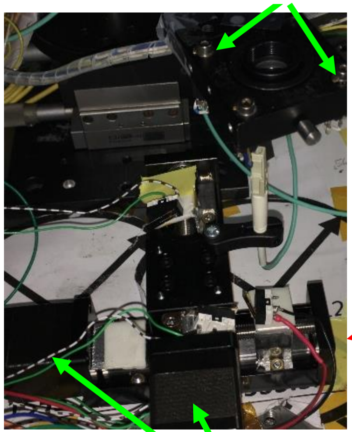
Complete Lab demonstrator @ TU/e

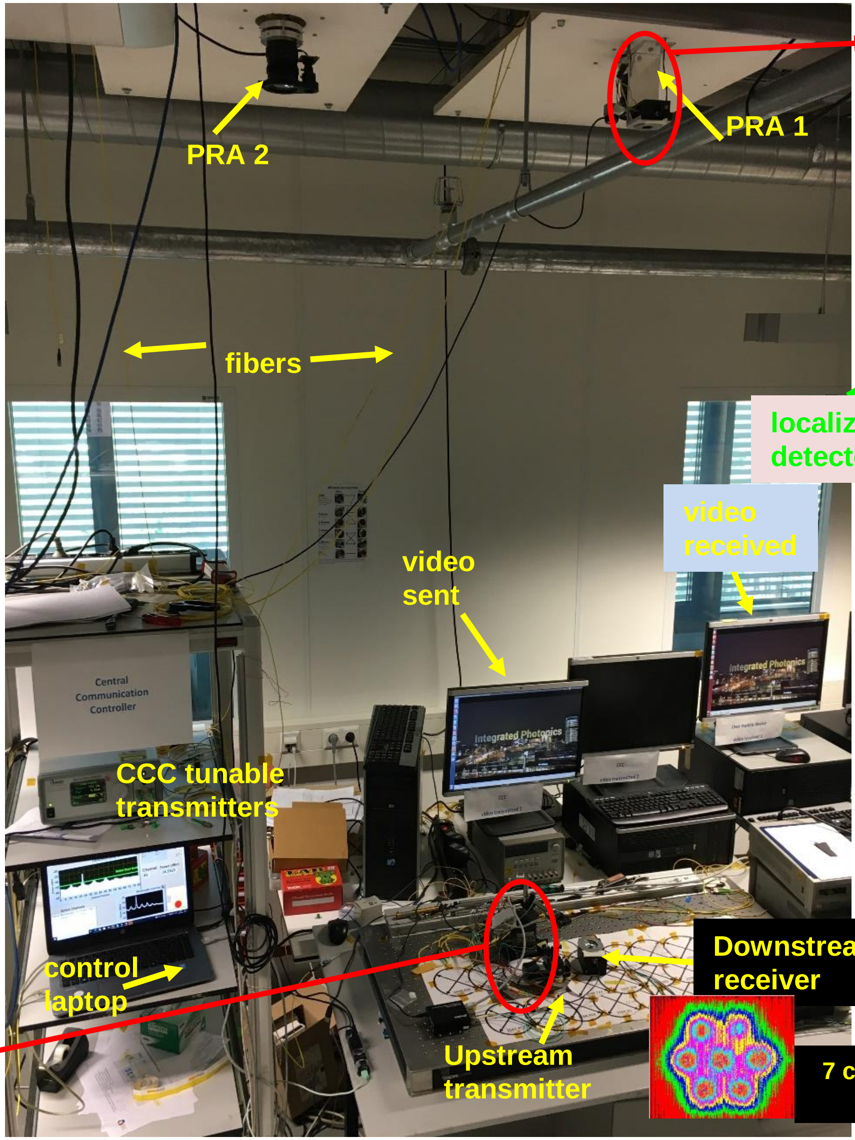
- Transfer of high-def video streams at GbE speed
- Two PRA-s + MEMS switch enabling path diversity for avoiding LoS blocking
- Up to 128 beams, ∅10cm
- FoV: 10 deg

GbE receiver, streaming video to a laptop/PC

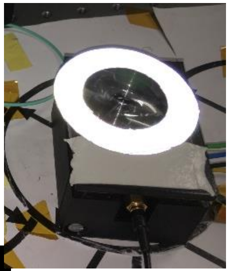


$f_1 \cdot (1-p_1)$





Downstream Tx.



7 cells captured with IR camera at 2.5m

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Possible End Users

- Business meeting rooms
- Class rooms
- Airport lounges, gates
- Public transport, in-flight/in-vehicle entertainment
- Hospitals, IC rooms
- Industry 4.0 manufacturing halls, warehouses
- Exhibition halls
- Data centers
- Residential home: fast internet connectivity, video delivery, ...

USP-s
- dense ultra-high capacity
- high power efficiency
- high privacy
- easily scalable to many users
- very low latency

Concluding Remarks

- Optical wireless communication systems can solve the imminent congestion of radio-based wireless systems: they offer huge amounts of extra spectrum, and can offload much of their traffic
- OWC systems offer enhanced privacy, and reliable operation in EMI-polluted environments (e.g., in Industry 4.0)
- Beam-steered OWC systems enable high-density delivery of broadband services and reduce energy consumption
- (Hybrid) photonic integration is needed for realizing cost-effective, compact, energy-efficient high-performance OWC systems. So far using off-the-shelf components → bulky devices
    - ✓ Compactness
    - ✓ Energy-efficiency
    - ✓ Cost-effectiveness
    - ✓ Mass deployment

Thank you for your attention!
Questions, comments, …?

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