Indoor Optical Wireless Communication using Steered Pencil Beams

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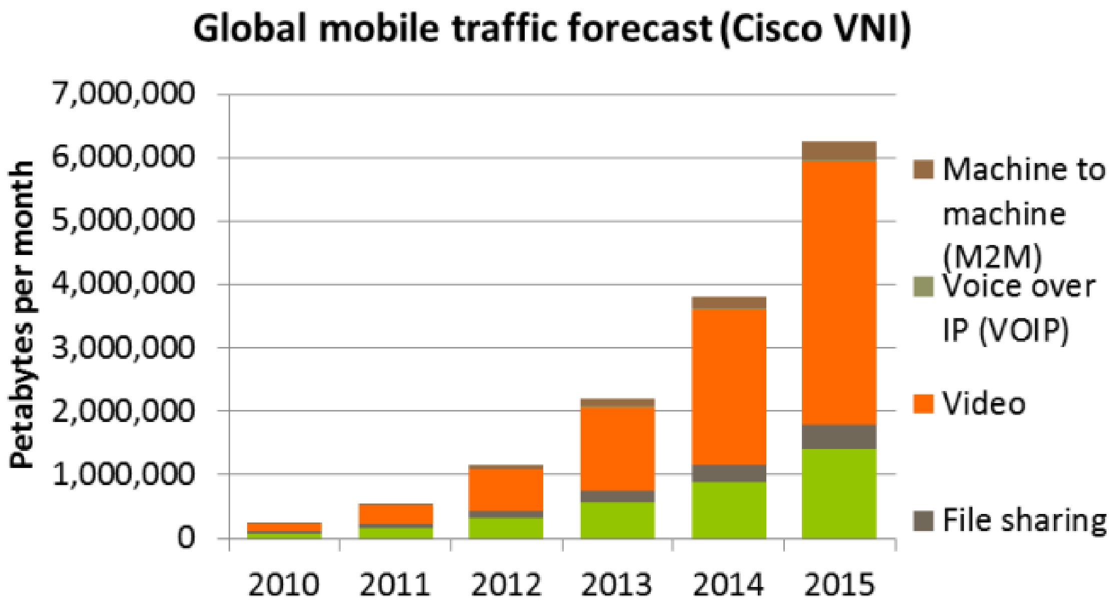
Outline

- Introduction – issues in indoor wireless communication
- Optical Wireless Communication
- Optical IR pencil beam 2D-steered communication system
- 2D optical beam steering techniques
- Experimental results
- Upstream communication
- Concluding remarks

Mobile traffic is booming, and largely coming from indoor

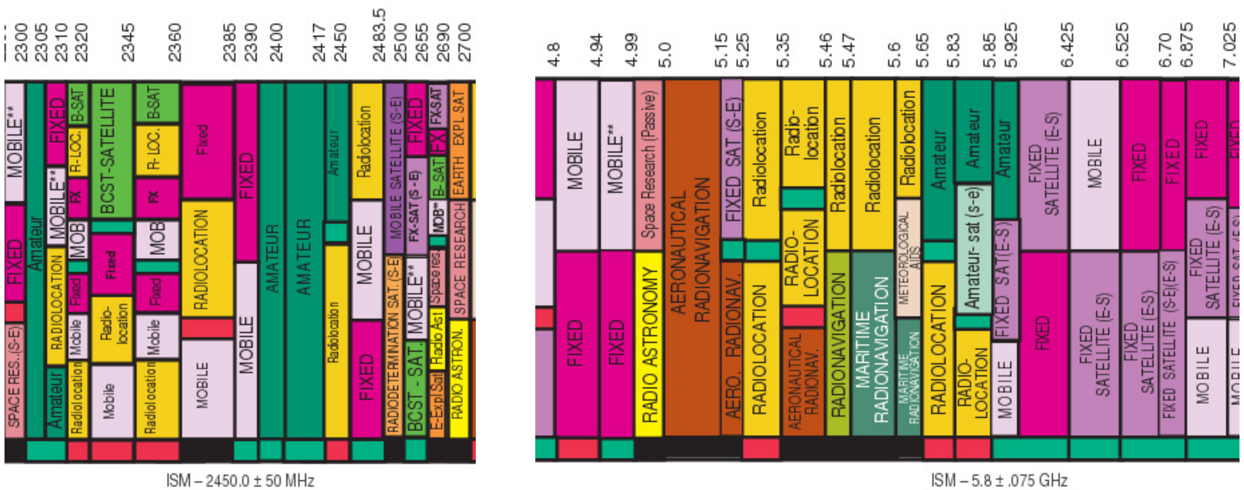


“According to a study from Cisco, subscribers use mobile data services 40% of the time from home, 25% from work, and 35% from public locations—with **at least 80% of the traffic coming from indoor locations**. Jaime Lluch Ladron of Telefonica expects that **95% of data traffic will come from indoor locations in a few years’ time.**”

[Beyond data caps - An analysis of the uneven growth in data traffic, by Monica Paolini (Senza Fili Consulting), 2011]

Indoor radio wireless communications is nearing its limits

- More wireless traffic is already coming from indoor than from outdoor devices
- Booming number of devices (‘Internet of Things’)
- Spectrum congestion
- Interference among devices
- High-capacity radio is power-hungry



Radio spectrum occupation 2.3-2.7 GHz, 4.8-7.0 GHz

Gbit/s wireless indoor access

Issues:

- radio spectrum congestion
- interference among wireless devices
- high power consumption

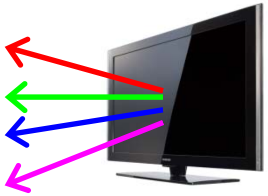
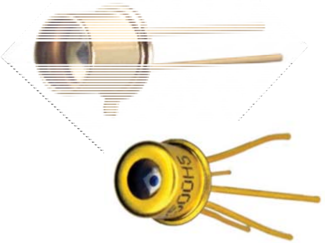
⇨ **Wireless pico-cells:**

- higher capacity per wireless device, frequency re-use
- energy savings DS and US
- dynamic capacity allocation, at fine granularity
- higher complexity

⇨ **Fibre-fed pico-cells,** with

- dynamic capacity allocation
- radio-over-fibre, radio beam steering
- **optical wireless communication, with optical beam steering**

Optical wireless communication – solving radio spectrum congestion

	VLC			IR
Transmitter / Receiver				
	Very low speed, dominated by the transmitter	Low speed, dominated by the receiver		
		Medium speed	High speed	Very high speed *

Visible range 400-700nm: 321THz
Infrared 1300-1600nm: 43THz

* IrDA aims for 5 and 10 Giga-IR

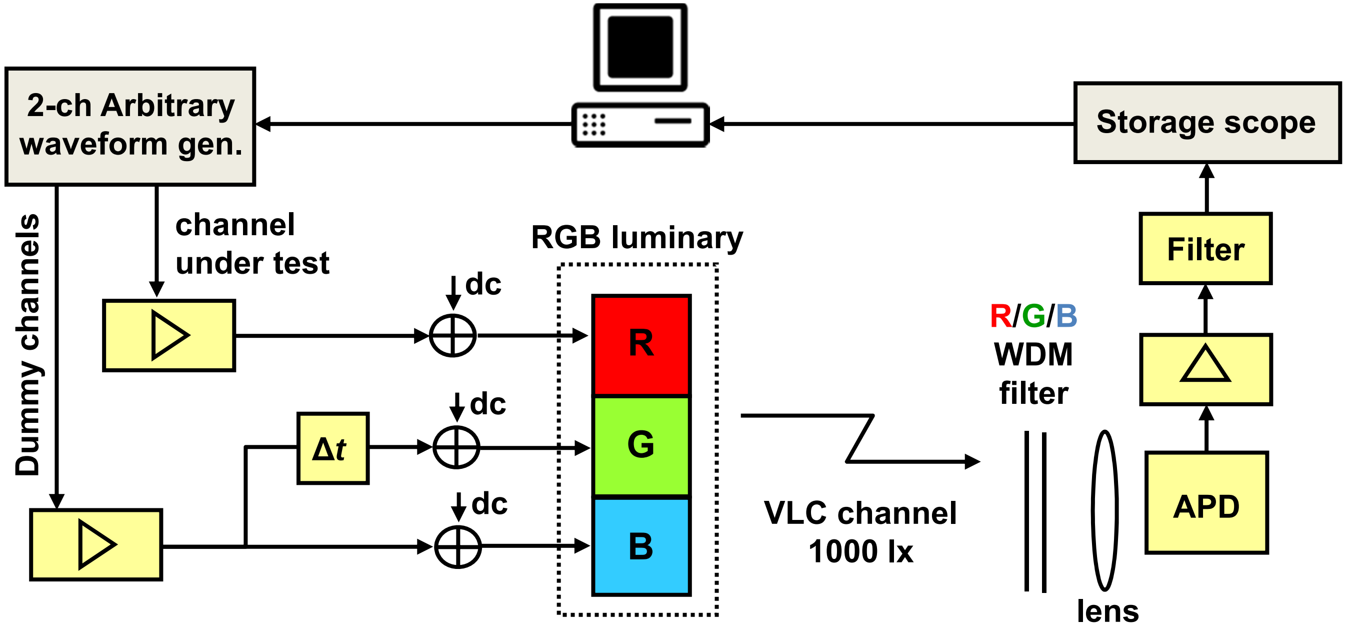
See also [K.-D. Langer - FHG-HHI, ECOC2012, Mo2G5]

Visible Light Communication (VLC)

- **Omnipresence of LEDs**: signaling and illumination
- LEDs offer significant potential for **modulation**
- **white LED** = blue LED + slow phosphor → blue filter at receiver
- Attractive for **offices, industrial settings, medical areas, public transport, …**
- Combination of illumination (or signaling) with data transmission → **data transfer as "piggyback"**
- Lab record using **single color LED**: 800 Mbit/s
- OMEGA project: 16 LED lamps covering an area ~10 m^2 (demo at ORANGE Labs, Feb. 2011)
- *Other advantages*:
  no EMI with RF, **unregulated spectrum**, **worldwide available**, **enhanced privacy**, …
- *Disadvantages*:
  - **illumination needs to be switched on for communication**, even in daylight
  - **devices in illuminated area share capacity**
  - **limited reach** (SNR$_{electr}$ ~ R^{-4} with distance R to LED)

See also [K.-D. Langer - FHG-HHI, ECOC2012, Mo2G5]

VLC using WDM - feasibility experiment



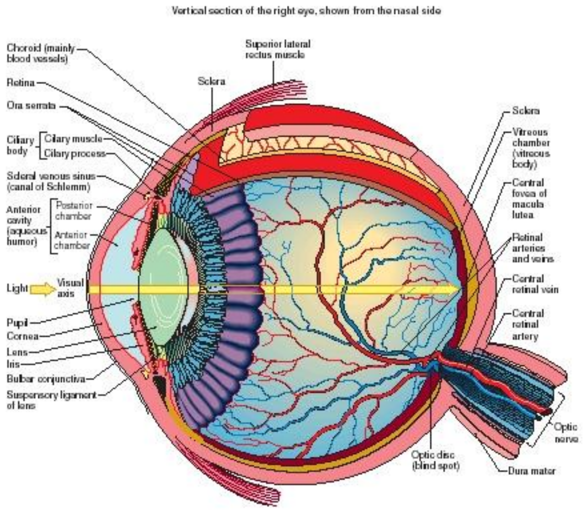
- Tx: RGB white LED module (3 WDM channels)
- Rx: WDM pass-band filters + photodiode
- Bit and power loading applied → throughput maximization
- Successive off-line processing of R, G, and B channels

→ RGB aggregate bit rate **3.4 Gbit/s over 10cm**

- Recently **3Gbit/s over 5cm** with 60 MHz blue 50um GaN LED and OFDM

[C. Kottke et al., ECOC2012, We3B4]
[G.Cossu et al., Opt. Exp. Dec. 2012]
[D. Tonev et al., PTL Apr. 2014]

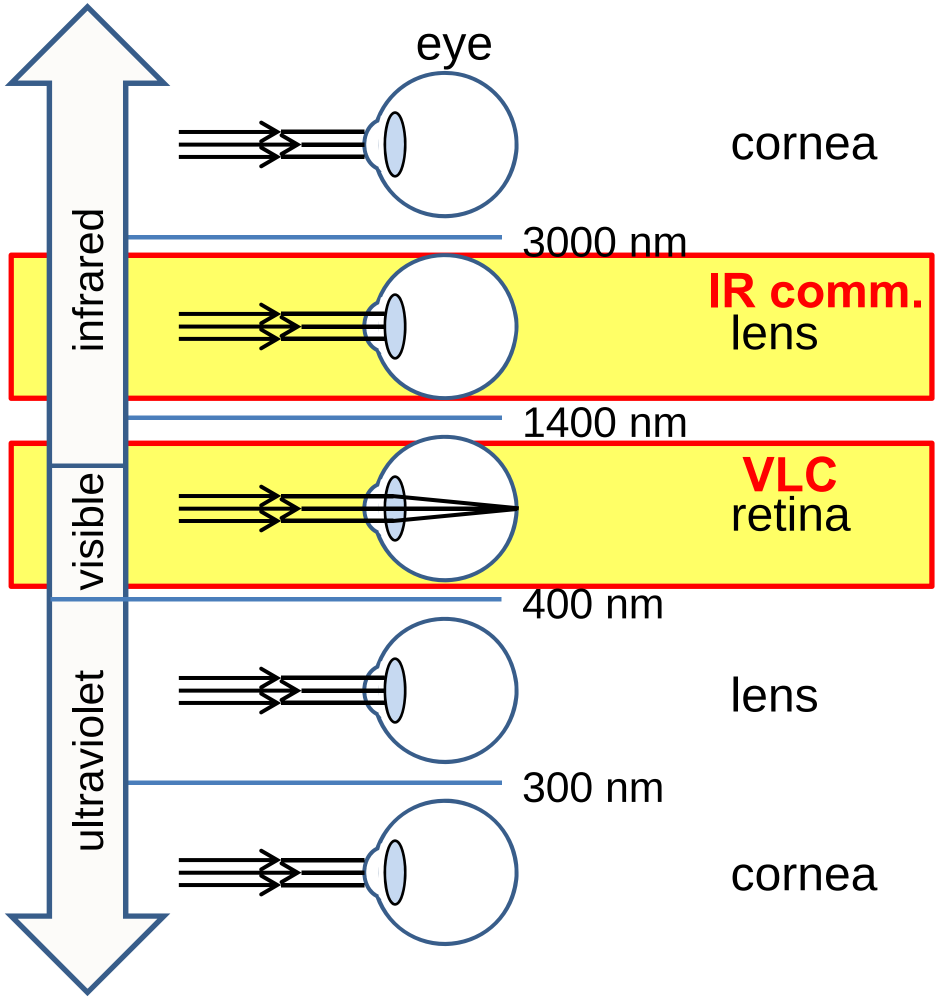
Eye safety



eye safety (ANSI Z-136 series and IEC 825 series)

	max. power @ λ=880nm	max. power @ λ=1550nm
Class 1	<0.5mW	<10mW
Class 1M	<2.5mW	<150mW
Class 3R	<500mW	<500mW

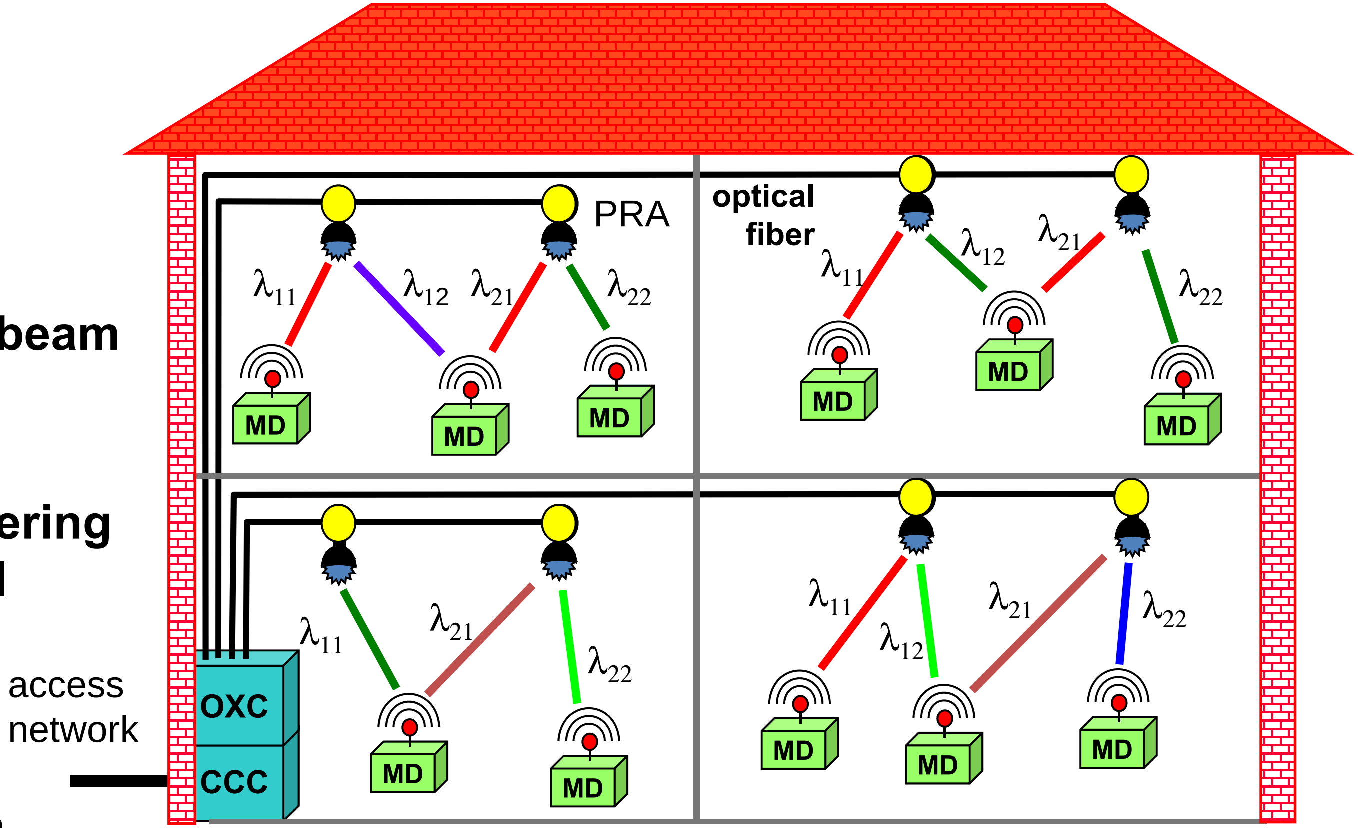
IR communication vs. VLC:
- allows higher optical transmit power
- higher photodiode receiver sensitivity
- Less interference from visible light



Optical beam steering in wireless optics

BROWSE's system concept:

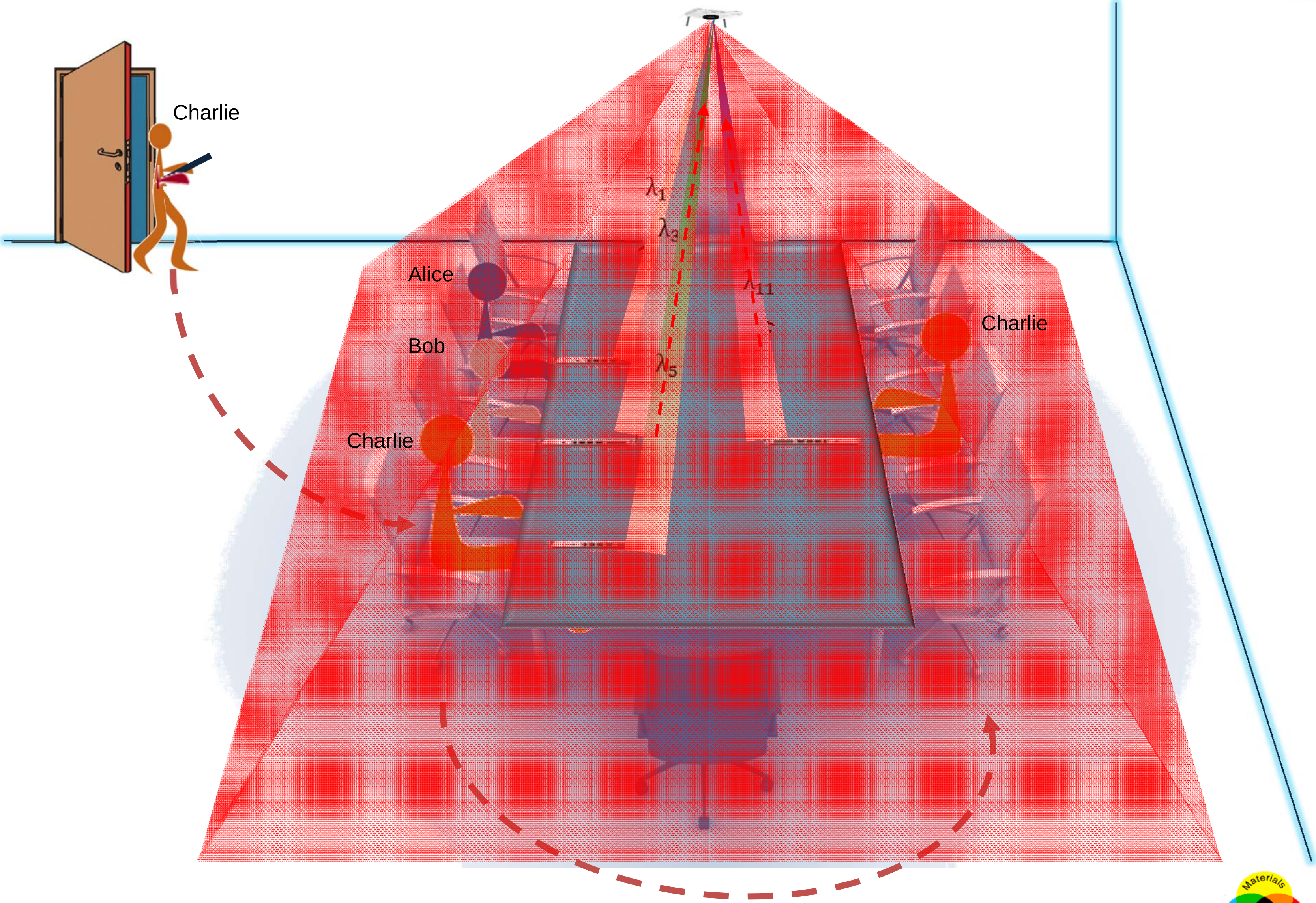
- **pencil beams →** no capacity sharing
- **IR λ>1400nm →** P_{beam} up to 10mW
- **passive diffractive beam steerer →** no local powering
- **λ-controlled 2D steering** → embedded control channel, can handle multiple beams
- *target*: **≥10Gbit/s per beam**



OXC = Optical Crossconnect
CCC = Central Communication Controller

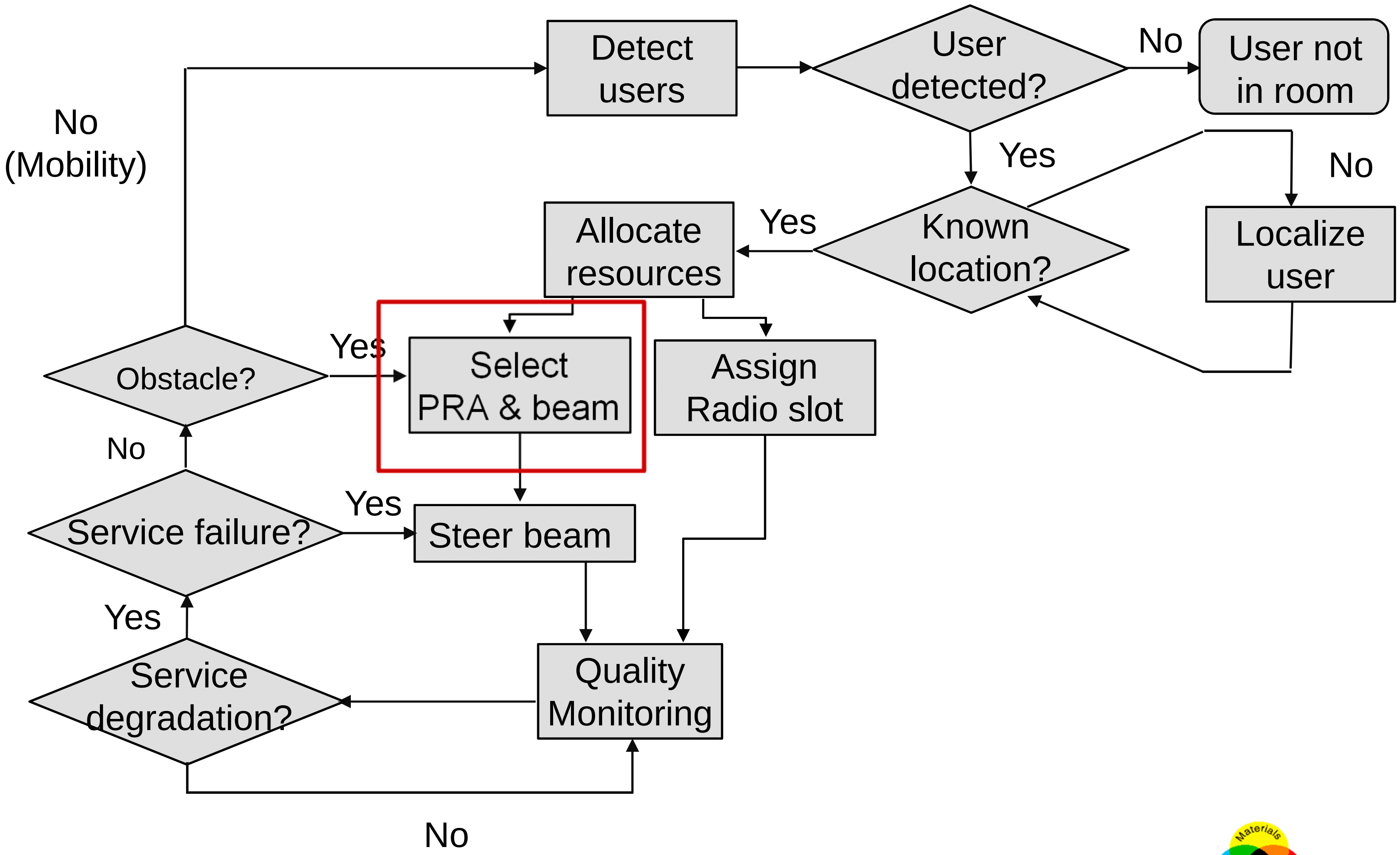
MD = Mobile Device
PRA = Pencil-Radiating Antenna
RN = Reconfiguration Node

Animation of BROWSE's beam-steering concept



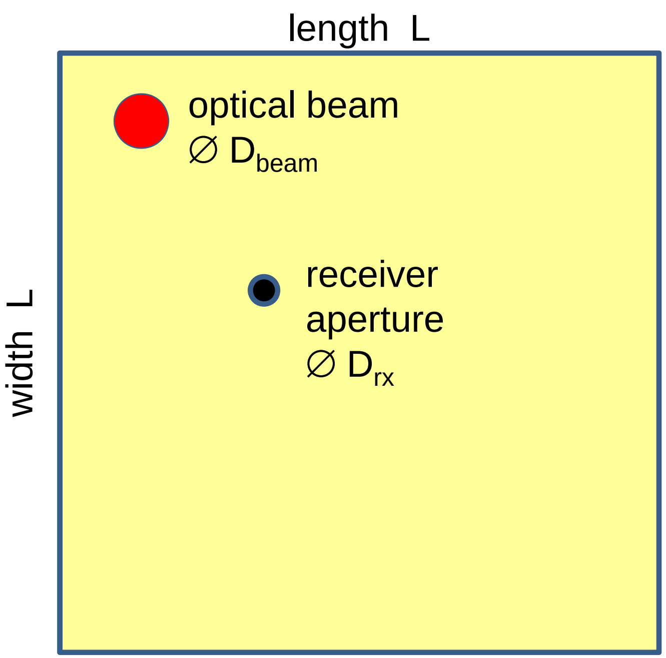
[courtesy of Joanne Oh]

Management loop for beam steering

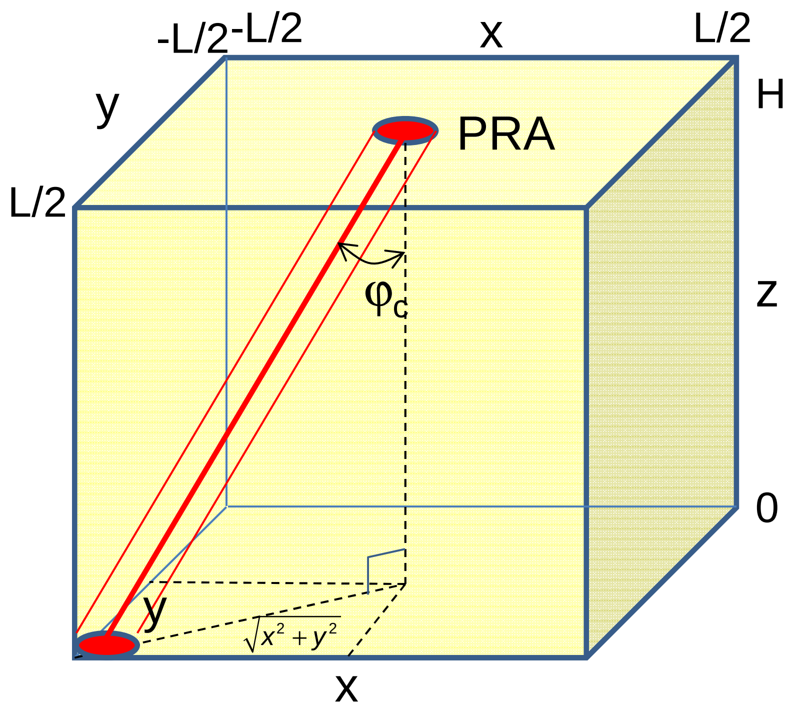


Dimensioning the optical-wireless system

Area to be covered



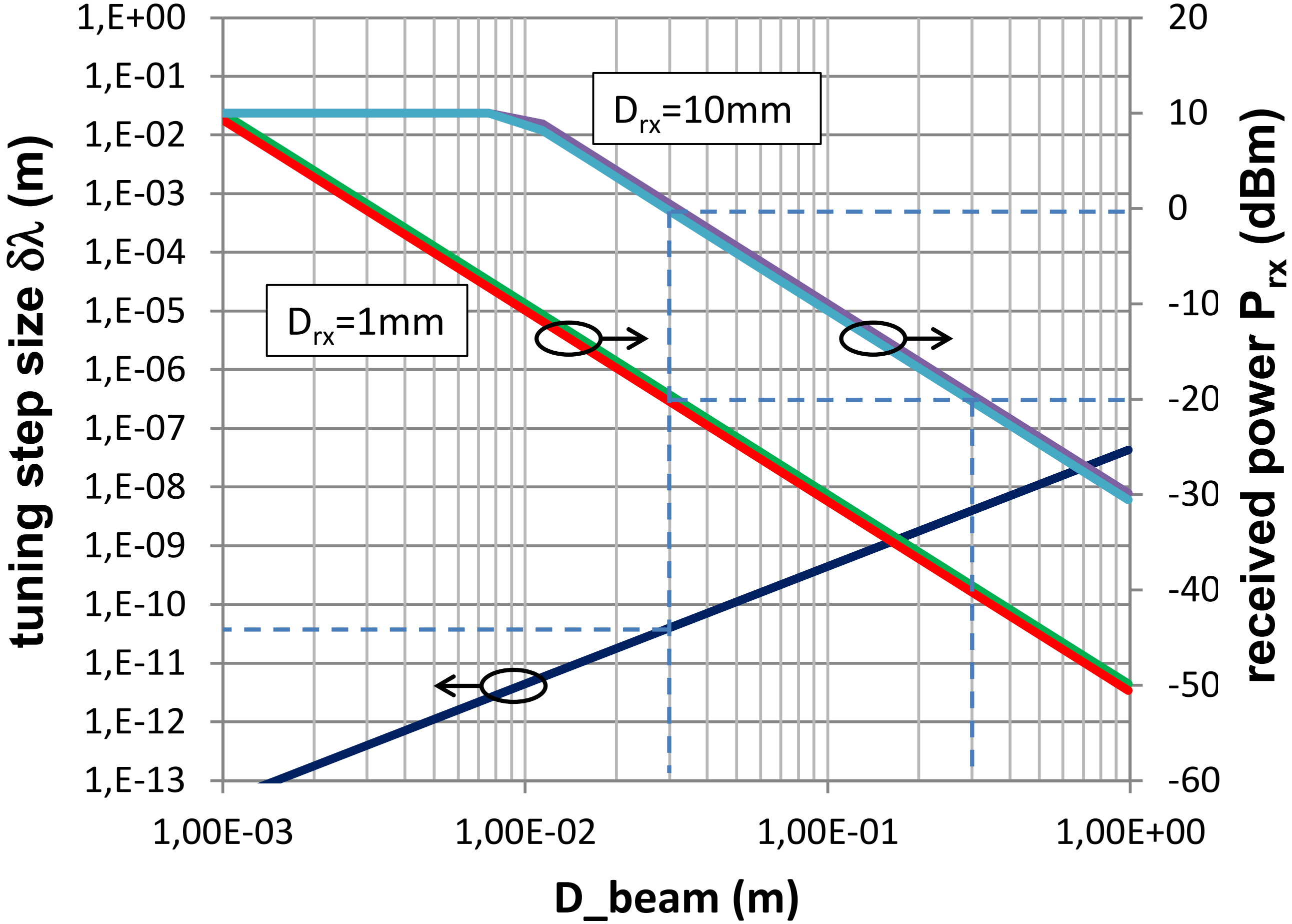
Room



- Number of scanning steps $N=(L/D_{beam})^2$
- Minimum received power in elliptical spot

$$P_{rx\_min} = P_{beam} \cos\varphi_c \frac{A_{rx}}{A_{spot}} = P_{beam}\left(\frac{D_{rx}}{D_{beam}}\right)^2 \left(1+\frac{L^2}{2H^2}\right)^{-1}$$

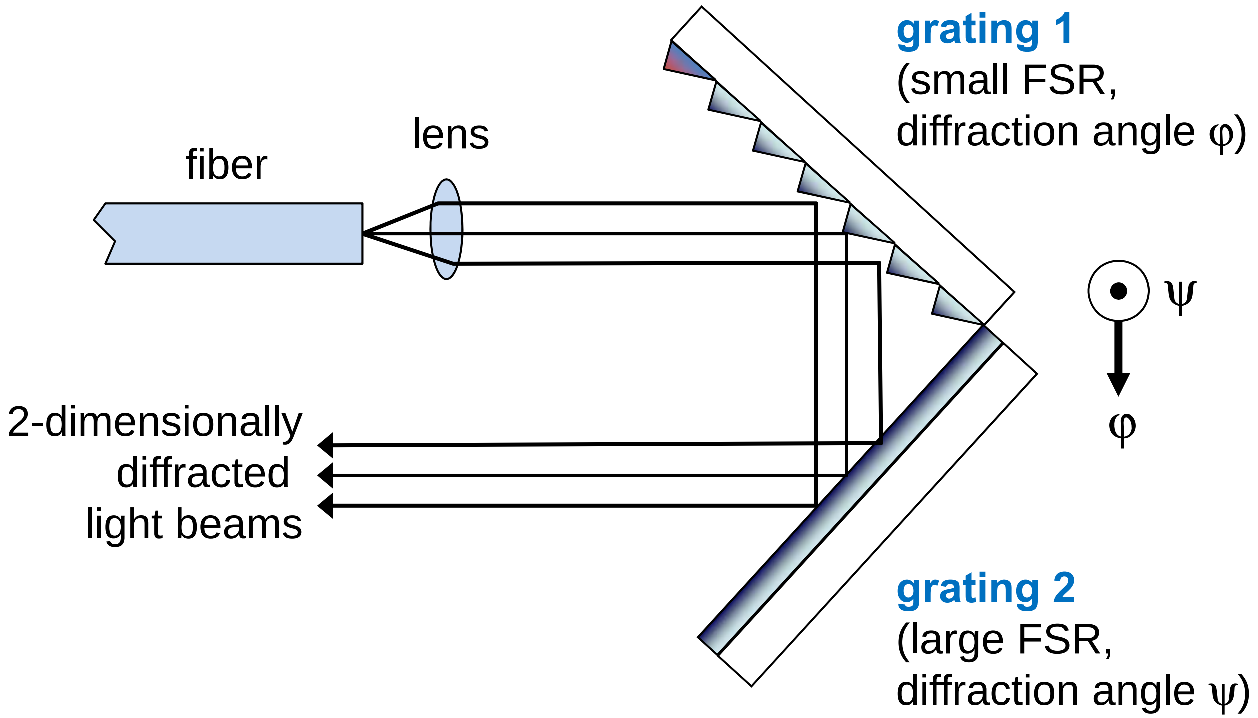
Choosing the beam diameter



P_{beam}=10mW
L=1.5m
H=2.5m

- when Rx sensitivity P_{rx_min}= -20dBm for 10Gbit/s data and $\delta\lambda$=50pm, D_{beam}=3cm for D_{rx}=1mm
- for D_{rx}=10mm the receiver sensitivity needed is relaxed to P_{rx_min} =0dBm

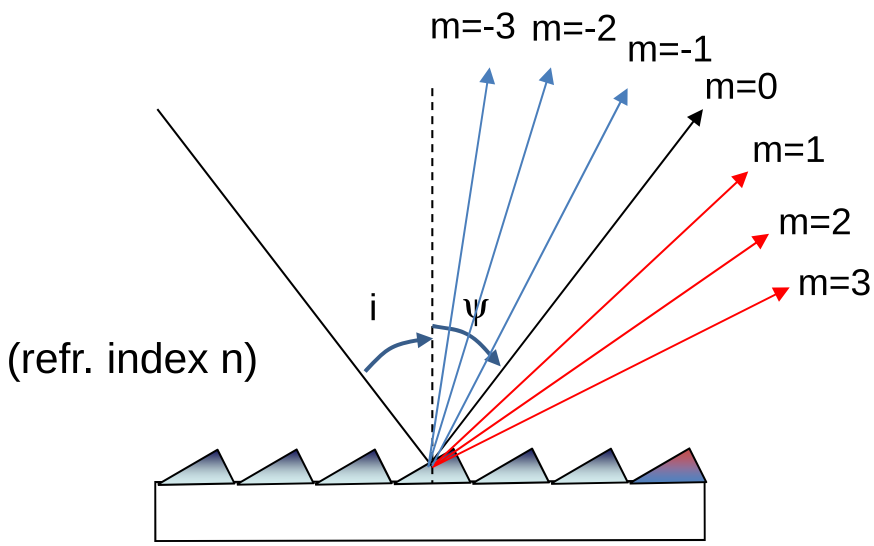
2D IR pencil beam steering with crossed gratings



- Fully passive device
- Deploys only wavelength tuning
- λ-scan range is smaller than FSR_2 , and comprises multiple FSR_1-s
- May simultaneously steer multiple beams (by multi-λ inputs)

FSR = Free Spectral Range, i.e. wavelength range between orders

Reflection grating operating in low order



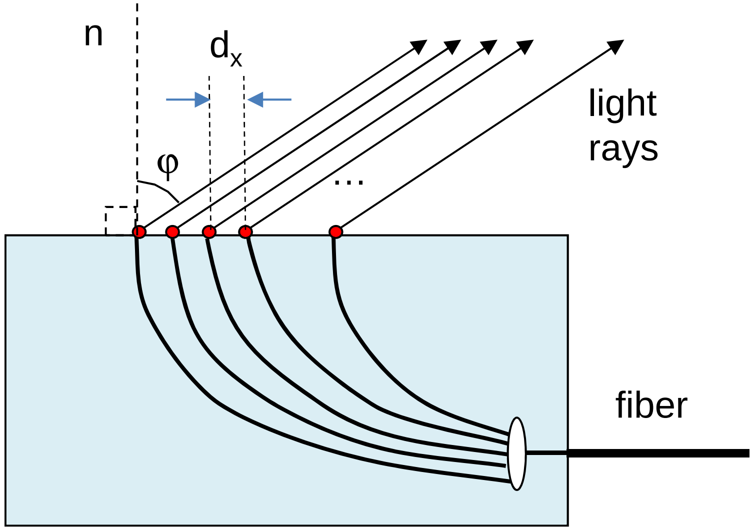
Grating equation $\sin\psi + \sin i = \dfrac{m \cdot \lambda}{d \cdot n}$

Free Spectral Range $\Delta\lambda_{FSR,m} = \dfrac{\lambda}{m-1}$

Max. angular tuning range
(by tuning over $\Delta\lambda = \Delta\lambda_{FSR}$,
starting at λ=1500nm)

N (gr/mm)	Δψ_max (deg)	order m	tuning range Δλ (nm)	θ_i (deg)	Δψ_max bound (deg)
50	22,80	25	63	72,39	23,07
55	23,97	23	68	79,66	24,07
60	25,11	21	75	79,90	25,21
65	26,22	19	83	72,83	26,53
70	27,32	17	94	63,71	28,07
75	28,36	16	100	66,93	28,96
80	29,37	15	107	68,21	29,93

Highly dispersive grating with small FSR



path length difference ΔL_x
between neigbouring waveguides

Arrayed waveguide grating

order

$$m = \frac{\Delta L_x + d_x \sin\varphi}{\lambda_i}$$

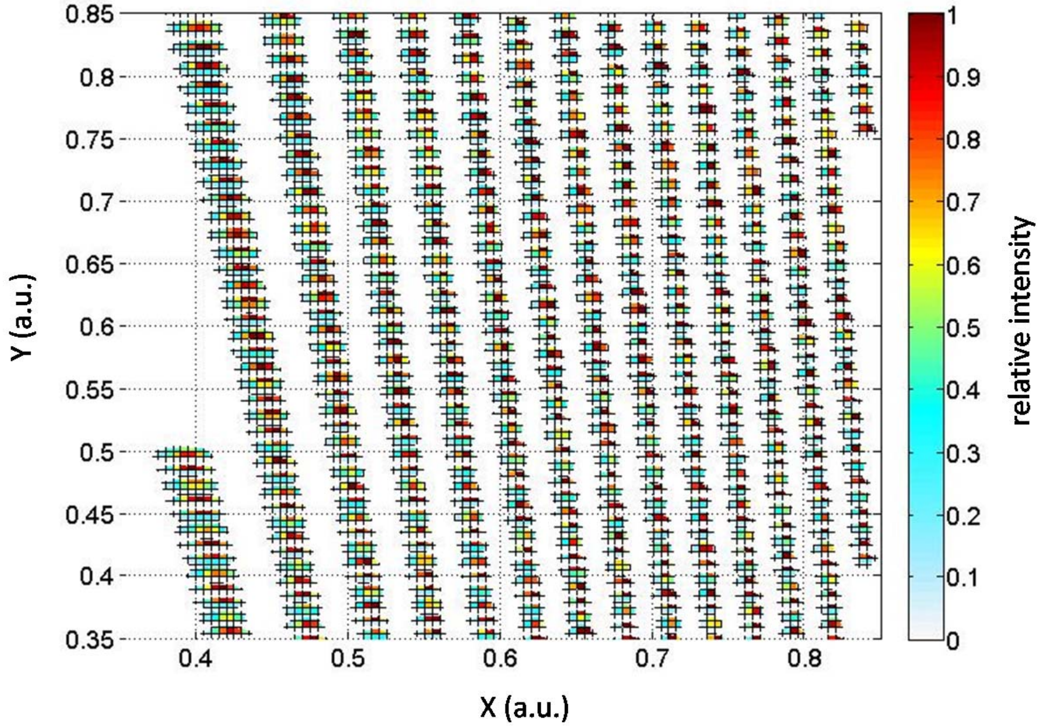
Free Spectral Range

$$\Delta\lambda_{FSR1} = \frac{\lambda_i}{m-1} = \frac{\lambda_i^{\;2}}{\Delta L_x + d_x \sin\varphi - \lambda}$$

Angular dispersion

$$\frac{d\varphi}{d\lambda} = \frac{m}{d_x \cos\varphi}$$

2D scanning by wavelength tuning



- **Waveguide grating 1:** N=50, d_x=6μm, ΔL_x=450μm → m≈300, $\Delta\lambda_{FSR1}$=5nm
- **Echelle grating 2:** M=50, Littrow mount θ_i=75deg, 83 grooves/mm
- **λ-tuning** with step size δλ=0.2nm from 1504 to 1574 nm (so over 14× $\Delta\lambda_{FSR1}$)

(simulation with MatLab)

$$I(\phi,\psi,\lambda) = I_0 \left[\frac{\sin\left(M \cdot \frac{\pi d_y}{\lambda}(\sin\psi - \sin\theta_i) \right)}{\sin\left(\frac{\pi d_y}{\lambda}(\sin\psi - \sin\theta_i) \right)} \right]^2 \cdot \left[\frac{\sin\left(N \cdot \frac{\pi}{\lambda}(d_x \sin\phi + \Delta L_x) \right)}{\sin\left(\frac{\pi}{\lambda}(d_x \sin\phi + \Delta L_x) \right)} \right]^2$$

Intensity of 2D angular diffraction pattern

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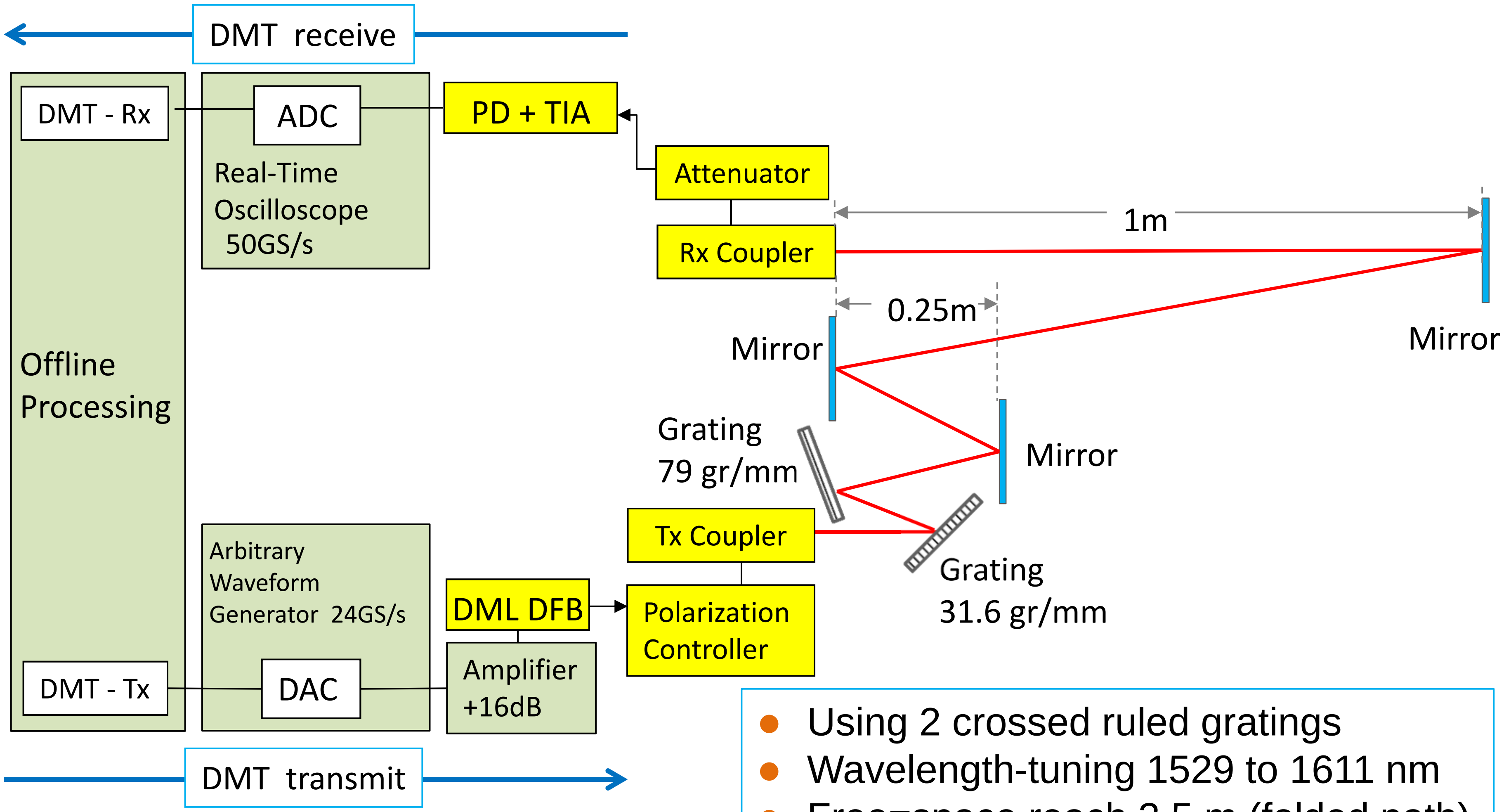
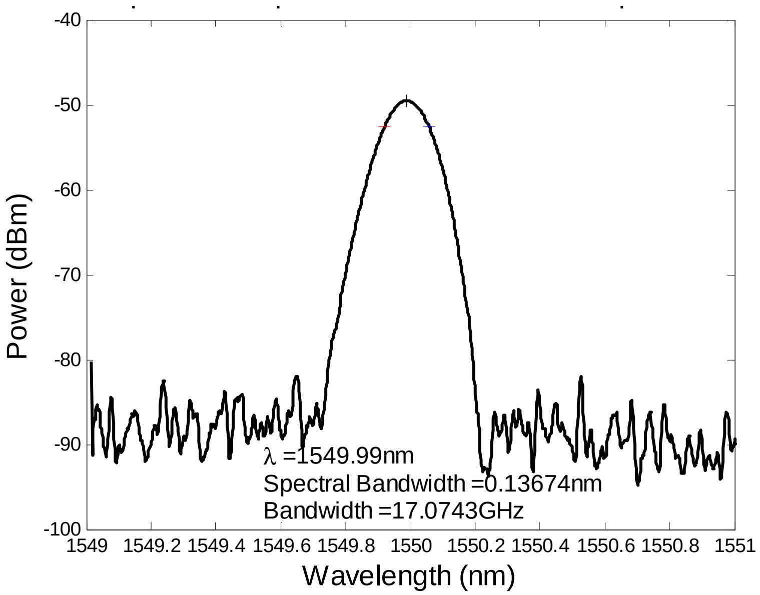
Experiment: 42.8Gbit/s 2D optical beam steering

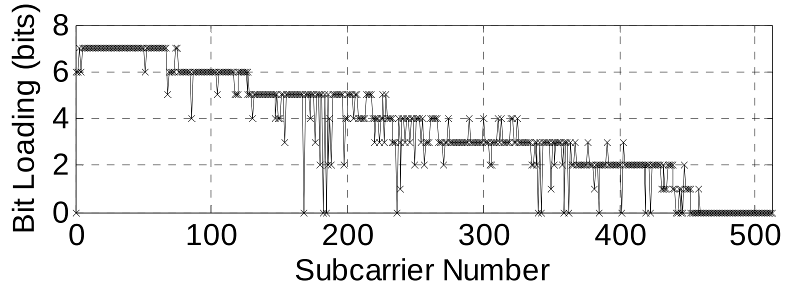


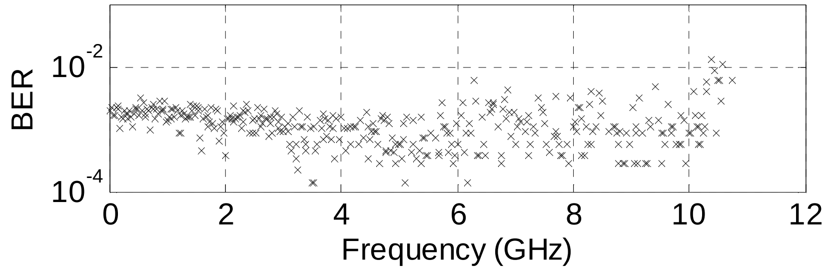
- Using 2 crossed ruled gratings
- Wavelength-tuning 1529 to 1611 nm
- Free=space reach 2.5 m (folded path)
- DMT modulation

[Joanne Oh, Eduward Tangdiongga, Ton Koonen et al, OFC2015]

Pencil beam channel characteristics







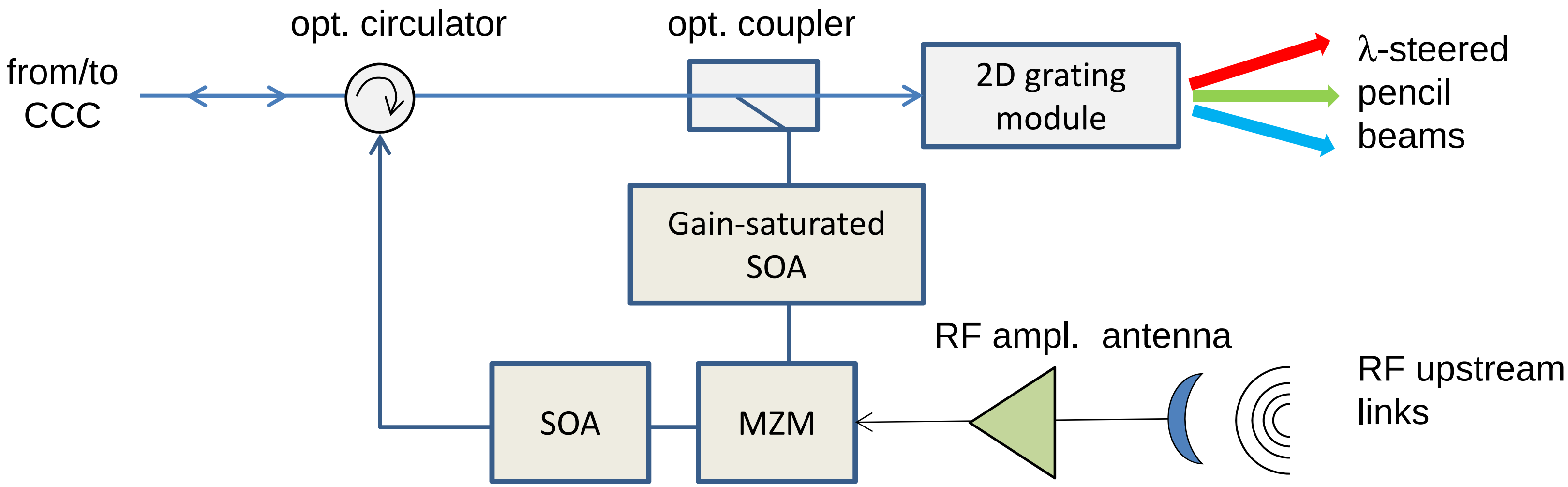
-3dB bandwidth

BW_{-3dB} = 17.1 GHz

Discrete Multi-Tone modulation

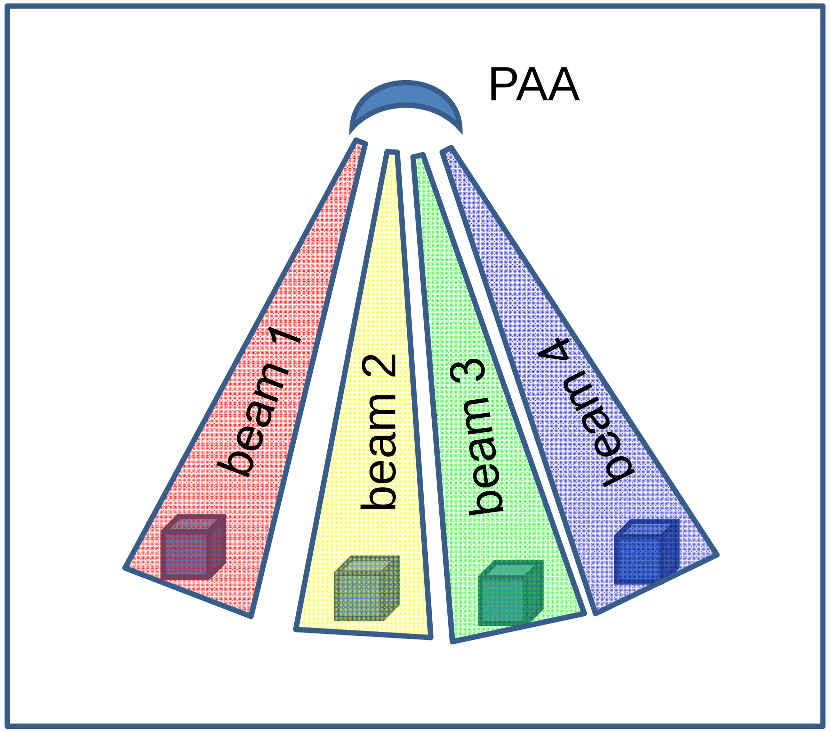
- 512 tones,
- adaptive bit loading
- max. 7 bits/symbol (QAM-128)

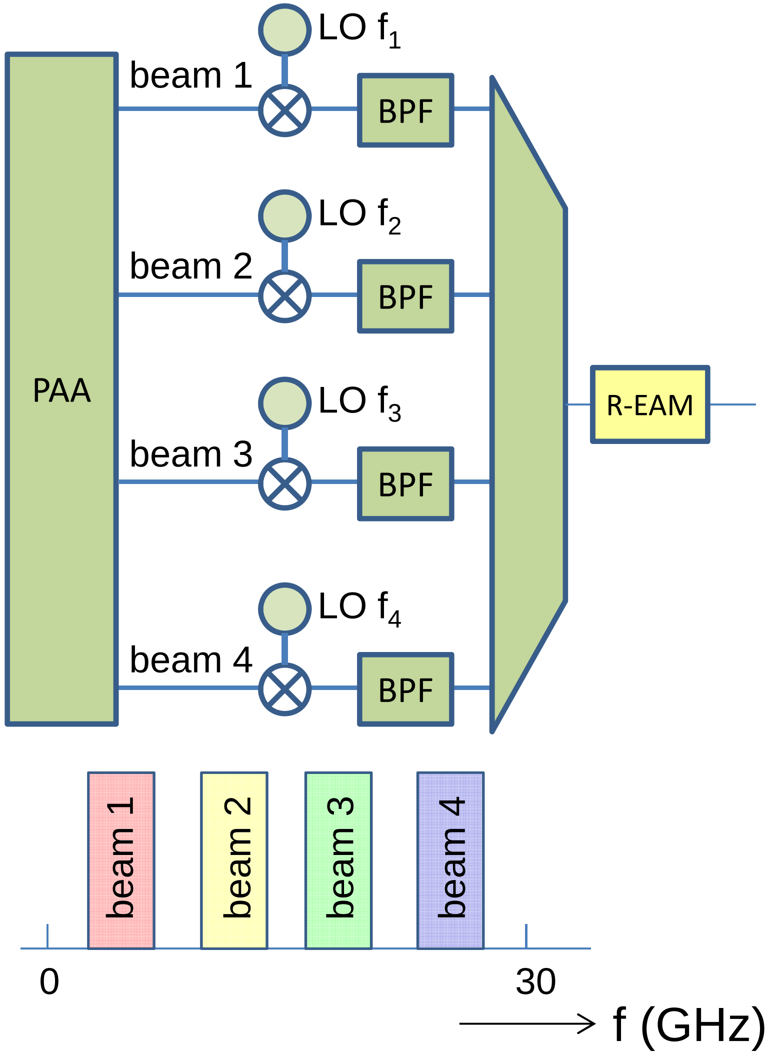
Radio-over-fibre upstream path



- **Re-modulation of downstream optical carrier**
- **Recovery of clean optical carrier:**
  - by erasing intensity modulation of downstream signal in gain-saturated SOA
  - *Experiment*: 2 DMT radio signals @ 10Gbit/s, up to QAM-32, downconverted below 11GHz

Radio-over-fibre multibeam upstream comm.





- Upstream RF beams, separated by phased array antenna (PAA)
- Each beam in 57-64GHz band
- Beams to be freq.-shifted + multiplexed

Concluding remarks

- **Optical wireless communication** is well positioned to solve the emerging radio communication bottlenecks.
- By deploying **infrared optical 2D steered optical pencil beams**, very high wireless capacity can be delivered in a highly energy-efficient way.
- 2D steered pencil beam communication at **42.8Gbit/s over 2.5m** using DMT techniques has been shown.
- A **crossed-grating passive structure** enables single-parameter λ-tuned 2D pencil beam steering, yielding easily scalable remotely controlled multi-beam high-capacity optical wireless communication.
- **Upstream communication**: in 60GHz band, using phased array antenna, optical carrier recovery and radio-over-fiber transmission.

European Research Council erc

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