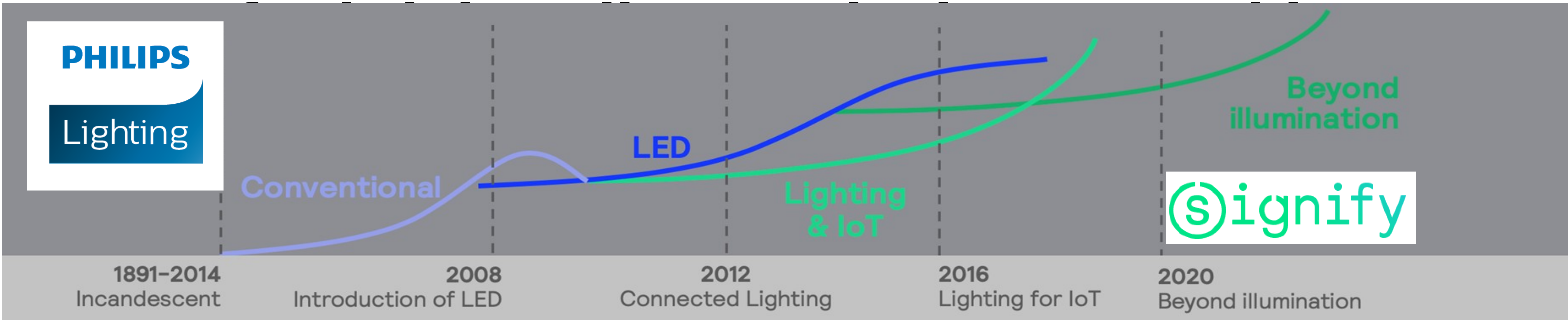
Reaching out to billions of client devices: Challenges and opportunities in very dense wireless networks.

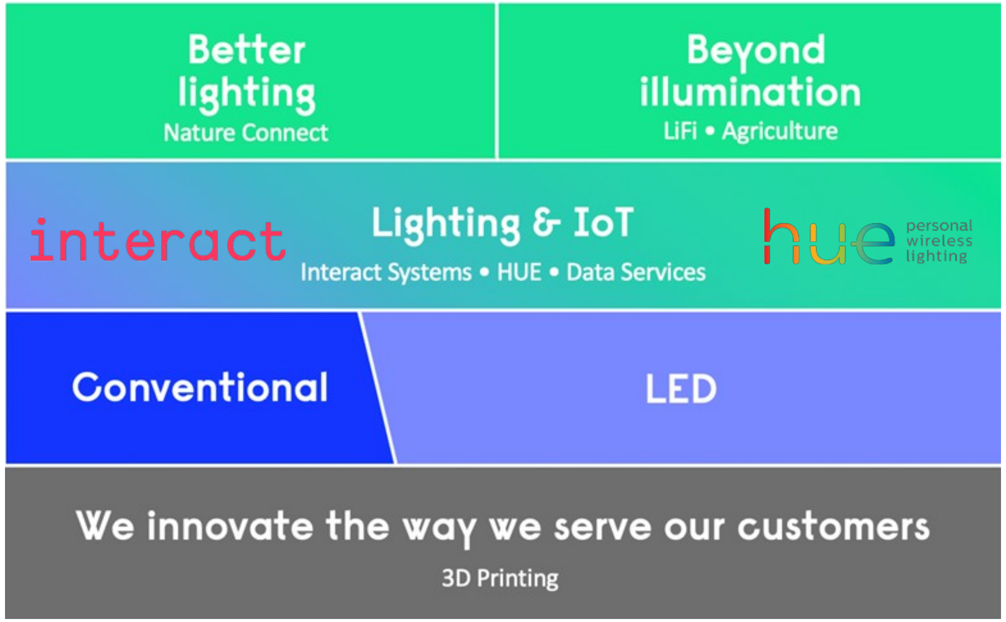
CONASENSE June 28, 2022

Prof. Jean-Paul Linnartz, Signify and TU/e Eindhoven

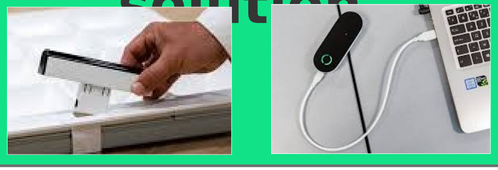
Signify: Our purpose is to unlock the extraordinary potential of light



Light has become a new intelligent language more essential everyday
Light connects and conveys a meaning
It is our signature
We are the Leader in Lighting
We are Signify



Lead in LiFi: providing the world's most advanced connectivity solution



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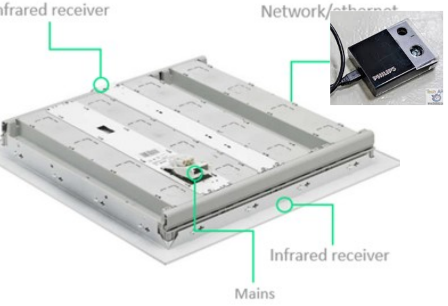
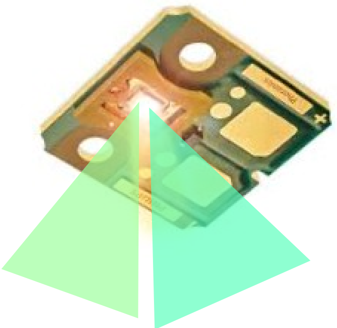
LiFi Roadmap

Fast
20 Mbit/s

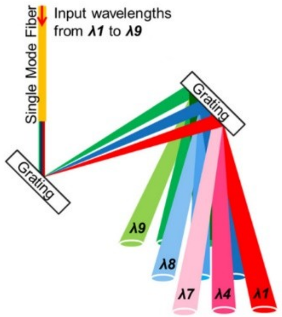


Fastest Commercial LiFi in the World
250 Mbit/s

Fast er
>1 Gbit/s



Faster & Denser
10 Gbit/s/m2



White LED — 2018

IR-LED — 2019

VCSEL — 2021

Steerable Laser — 2025

Customer and Market demand
- Faster
- Denser, Better QoS performance
- Smaller (integrate into smart phone)
- Price

To maintain pace of innovation we need
- From LED VCSELs Laser
- From wide angle sectorized emitters steerable pencil beams

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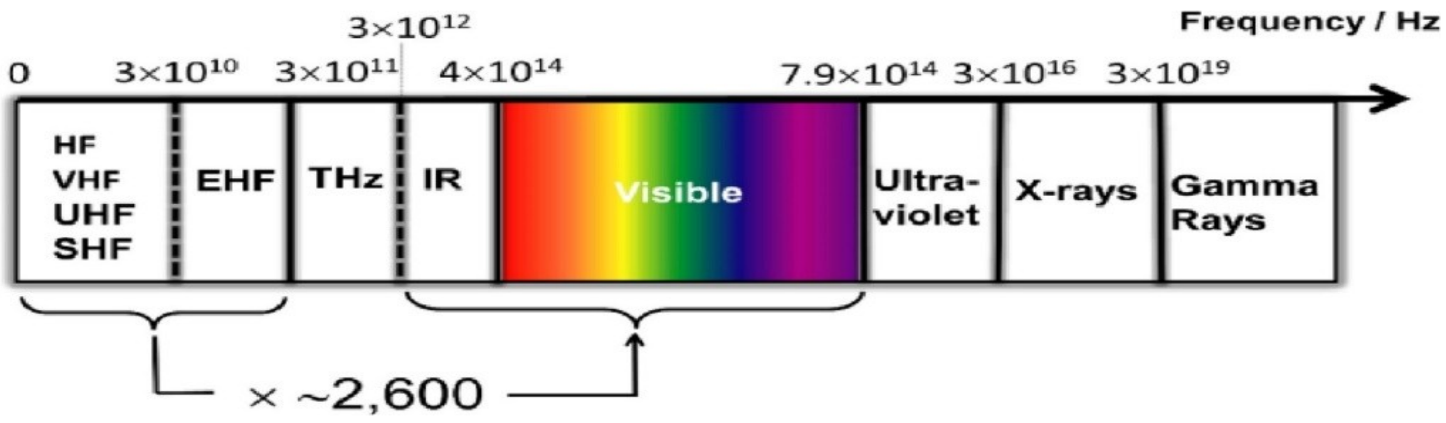
The Potential of Optical Wireless Communication (OWC, LiFi)



- The OWC spectrum is 2,600 time larger than the entire radio spectrum
- One VLC LED link uses as much as 1000 times the entire radio spectrum for just one user @ 300 Mbit/s, wastefully, at an efficiency of only millibit/s/Hz [JPL]

Is the promise of OWC in the width of the spectrum

or

in the reusability of the spectrum?

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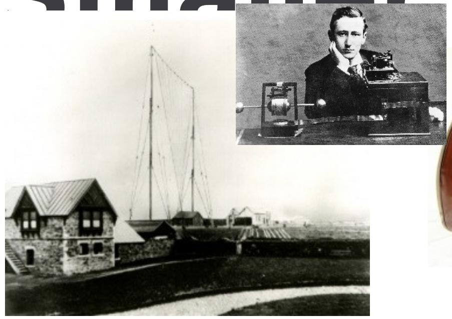
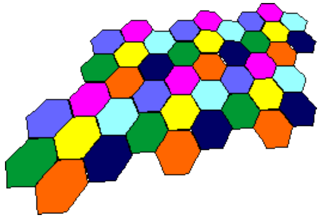
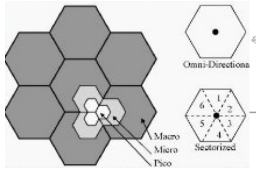
Consistent Trend : Denser Reuse, Smaller Cells





20s	60s	70s	80s	90s
Trans Atlantic Morse Code	Clear AM channels	FM Radio	Cellular Reuse	Cell splitting

W

LEDs

OWC with LASERS

 # Channels **Channels/Hz** **Channels/Hz /country** **Traffic/Hz/km²**

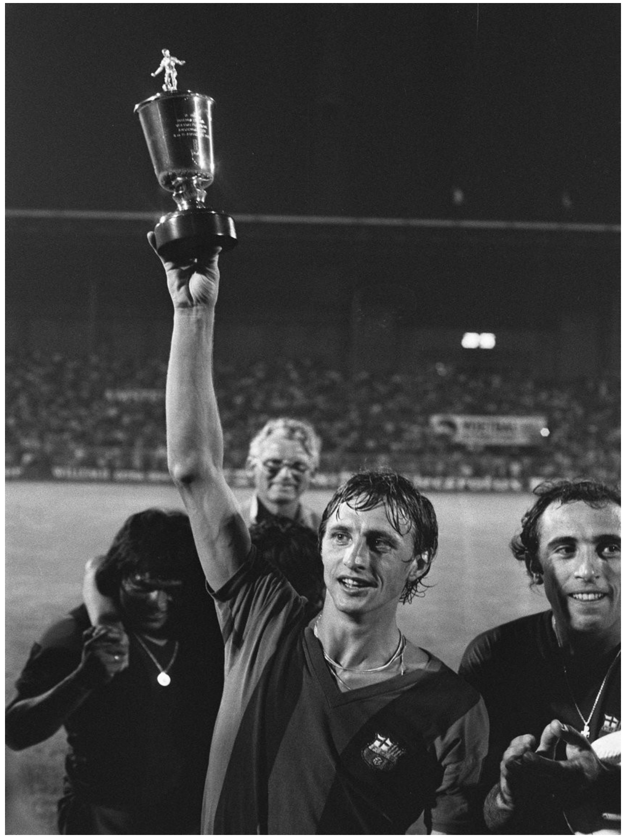
Coverage area, "cell" size

5000 km 300 km 30 km 3 km


Exponential Densification

“Every disadvantage has its advantage”

	Disadvantage In 1993	Advantage In 2020
Light does not go through the wall	Coverage is Limited	Interference is limited, denser reuse, more users
		Higher QoS Low latency
		Security


“Every disadvantage has its advantage”

Limits to Scalability
How many users per m² can we handle?

Coldplay: Broadcasting to 50,000 wristbands receiving from one powerful transmitter,
1-to-50,000, No Networking

300 hue lamps at Light and Building, Frankfurt 2016
Need two-way protocols

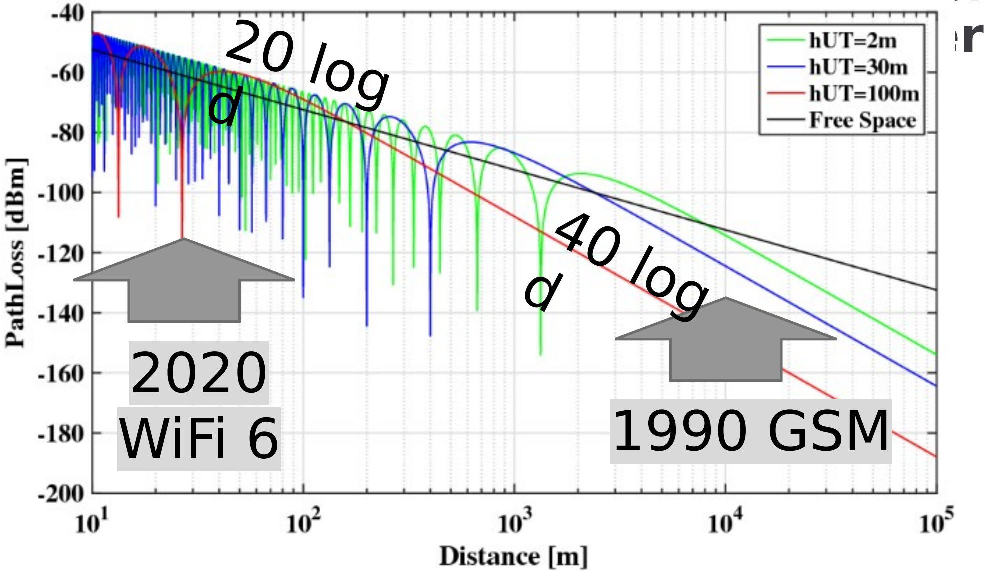
On the scalability of RF Radio Networks

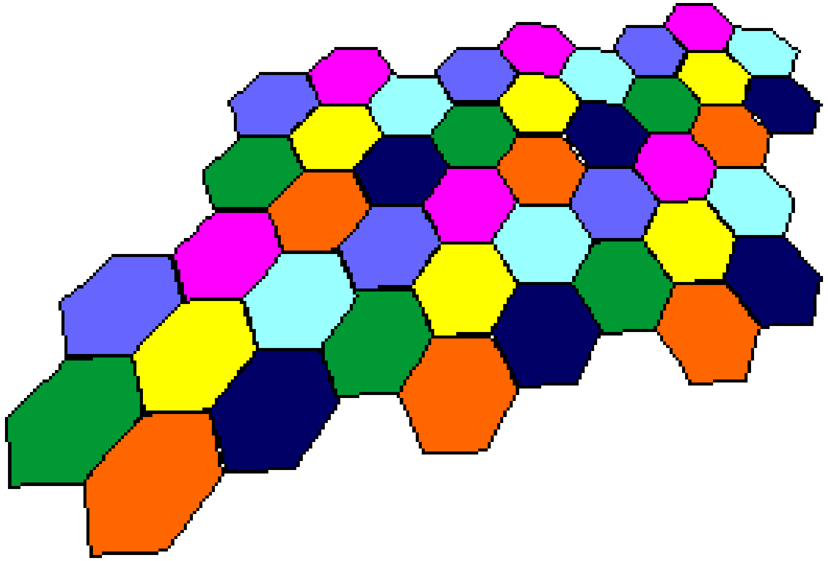
In the 1980’s cellular frequency reuse was introduced. The idea is to use the same frequency in an adjacent area. This greatly increased density: Mbit/s/km²/MHz

As the path loss in a cell phone network typically reduces with the third or fourth power of the distance,

at the cell edge the signal is much stronger than that of the nearest interferer

In good approximation, the interference only





Can we infinitely scale-up user density by cellular reuse?

The latter assumption becomes very inaccurate for networks that experience free-space loss, where the interference reduces with the square of the distance

Short range: 20 log d (Free space loss)
Long range : 40 log d (Plane earth loss)

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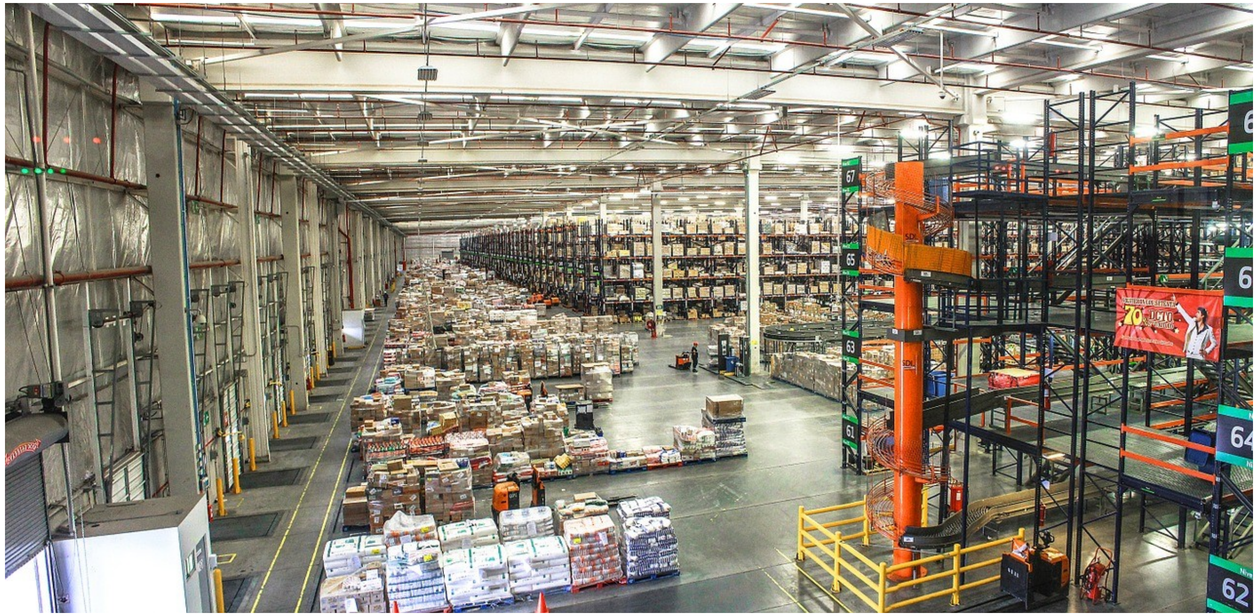
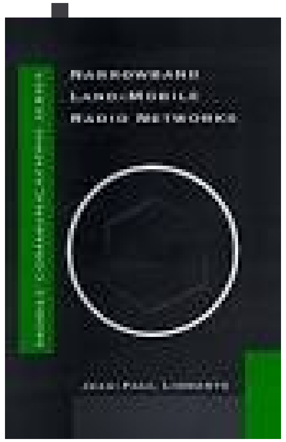
The performance of very large radio systems collapse if the path loss is close to 2, thus 20 log d

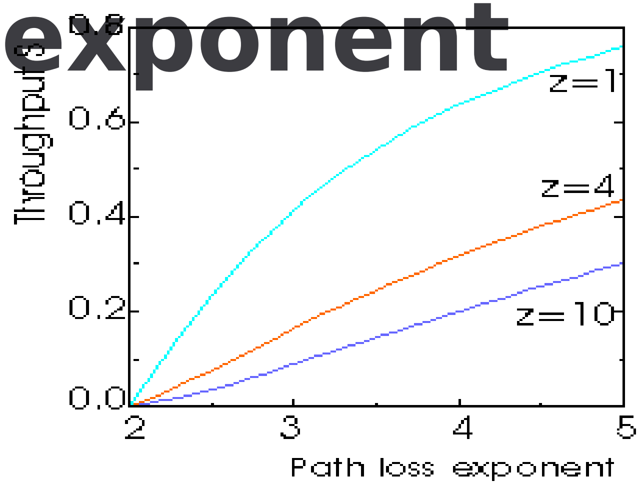
- As we move to higher density, the cell sizes shrink, this makes situations with 20 log d more common place
- Examples are :
  - Parking garage (13 log d)
  - Airplane cabins (energy trapped inside)
  - Very dense office spaces with a need to place mutiple AP within line-of-sight
  - Industry halls
  - Logistic distribution center
- In free-space settings with short distances, adding more access points does fundamentally not help

- Light (and MM-wave) can be made to have directional beams, pointed downwards. This helps to shield-off cells.



Scalability of RF Networks depends on path loss exponent

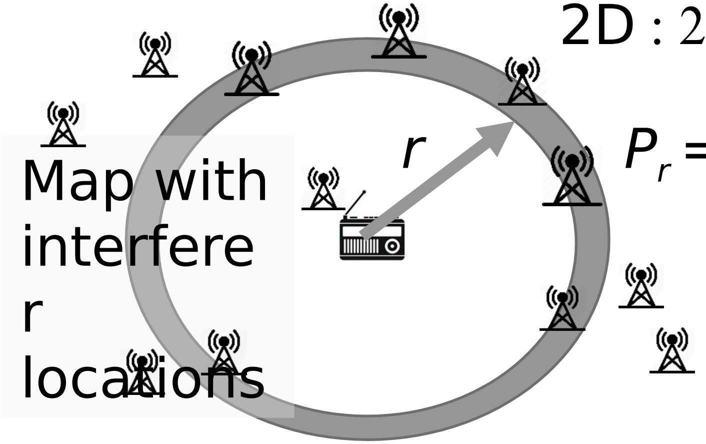




Narrowband Land-Mobile Radio Networks | Jean-Paul Linnartz, 1993

Number of interferers in 3D : $4\pi r^2\, dr$

2D : $2\pi r\, dr$



$P_r = P_T / r^2$

$$Interference = \int_0^{\infty} \frac{2\pi r}{r^2}\, dr \rightarrow \infty$$

For free space loss ("20 log *d*" or *beta* = 2), the throughput of the ALOHA network reduces to zero. The explanation is that the total interference power becomes infinite in any time slot.

The signals from users on a ring at distance *r* are attenuated proportionally to r^{-2}.

The number of users on the ring is proportional to *r*.

So, the total interference power is proportional to 1/*r*.

If we assume that users are present in an infinitely extended area, the total interference power is proportional to the integral from 0 to infinity over 1/*r*, which is known to diverge.

Hence, every packet sees an infinitely large interference power, so it has zero probability to capture the receiver.

NB : reducing power does NOT help.

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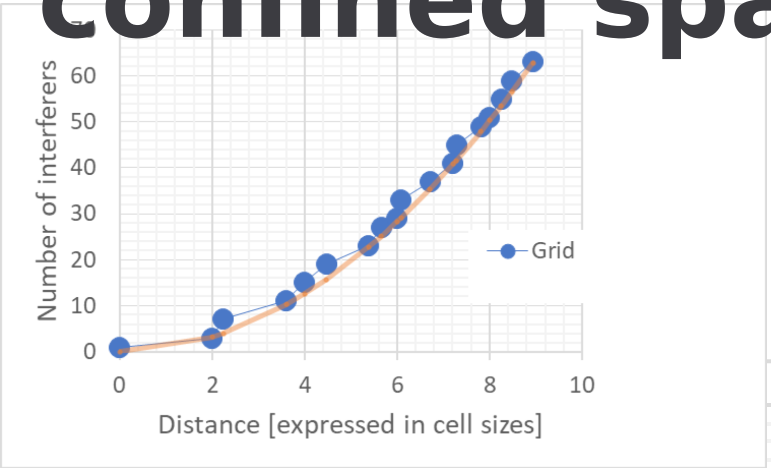
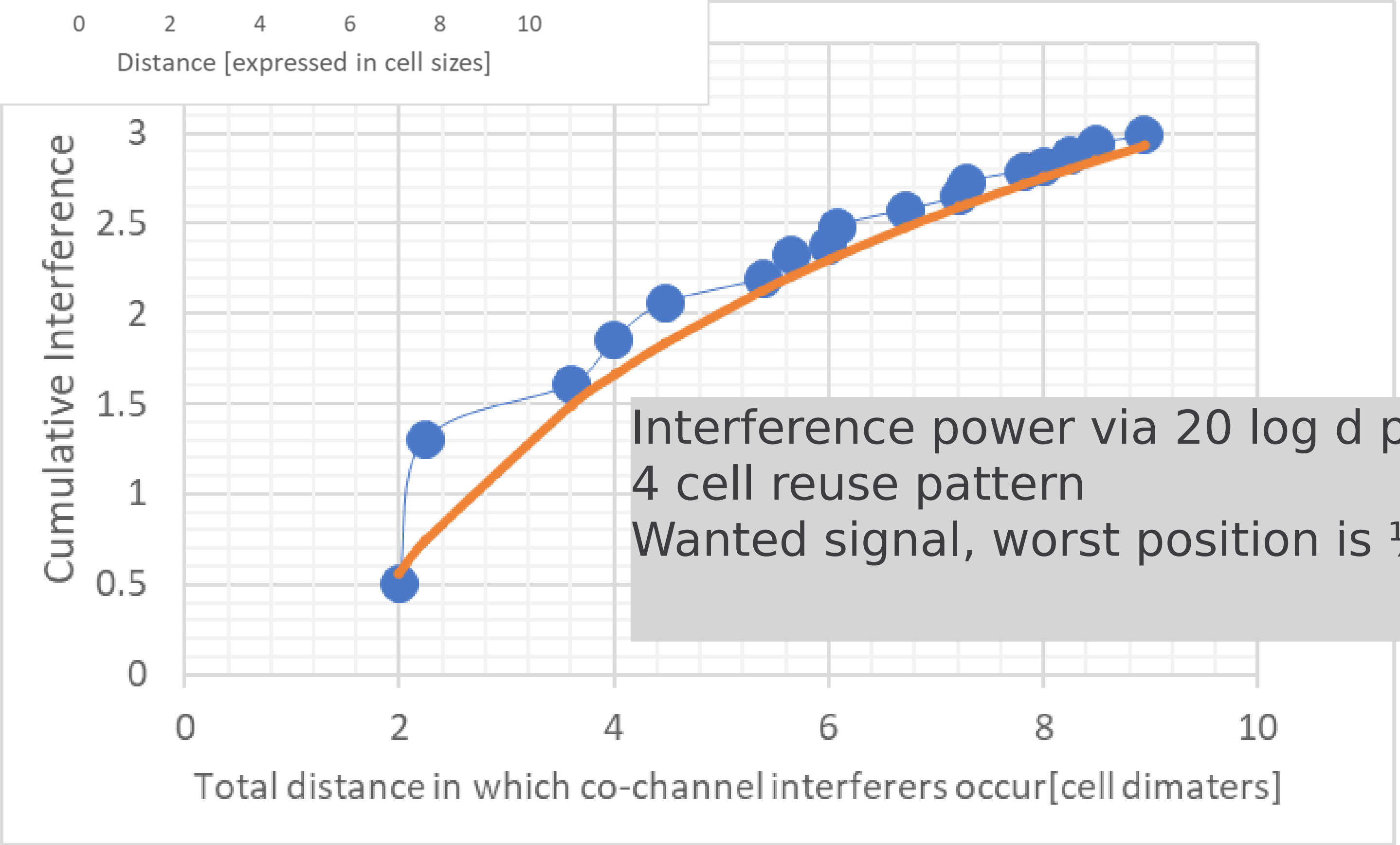
Cumulation of radio interference in confined spaces

- In an environment in which the signal levels do not vanish rapidly with distance, the interference levels rise too high

- MIMO and interference cancellation cannot eliminate (too) many weak interferers

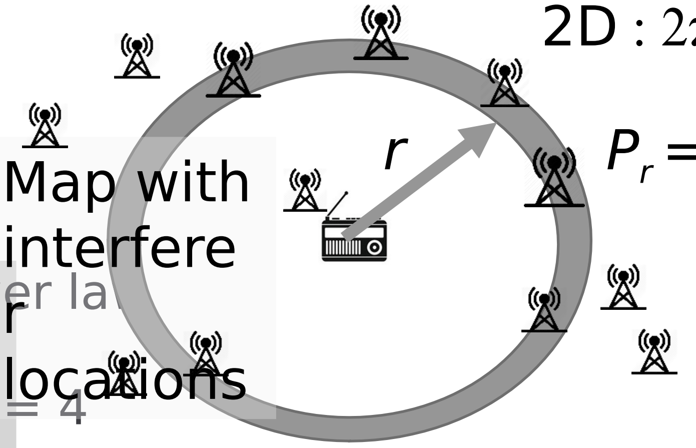




Interference power via 20 log d power law
4 cell reuse pattern
Wanted signal, worst position is $½^{-2} = 4$

Number of interferers in 3D : $4\pi r^2\, dr$

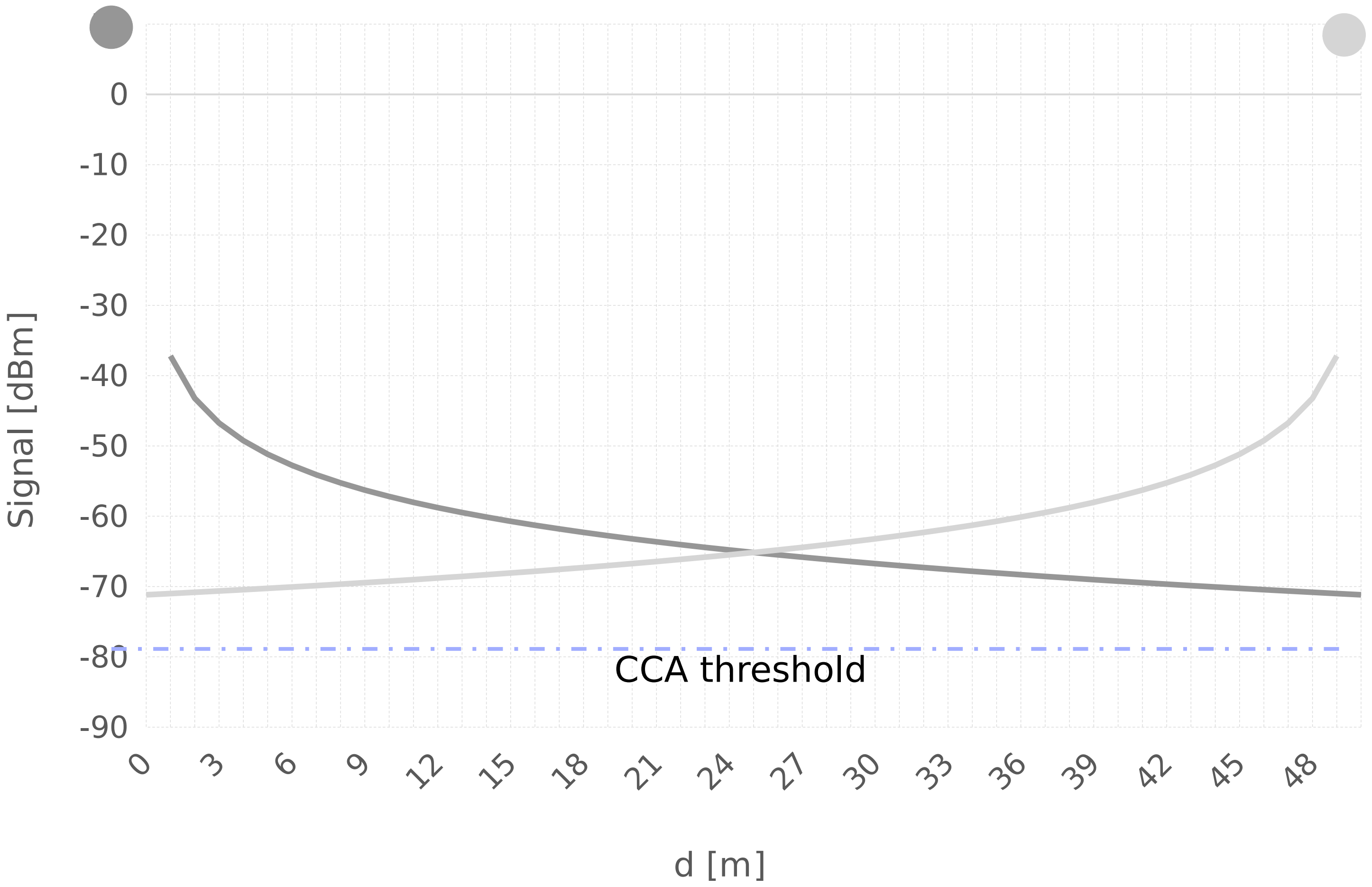
2D : $2\pi r\, dr$



$P_r = P_T / r^2$

$$Interference = \int_0^\infty \frac{2\pi r}{r^2} dr \rightarrow \infty$$

Wi-Fi 6 OBSS_PD allows for adjusting the CCA threshold (e.g. AP: 10 dBm, CCA: -72 dBm)



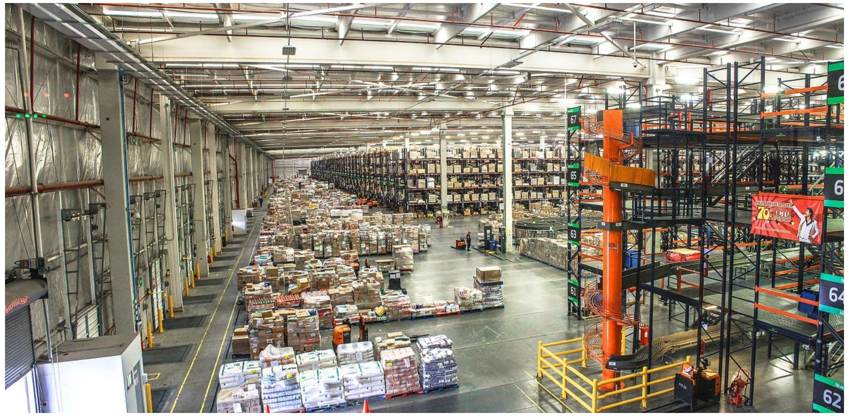
Wi-Fi Reuse in a factory hall of 50 m is possible if

- **We reduce power**

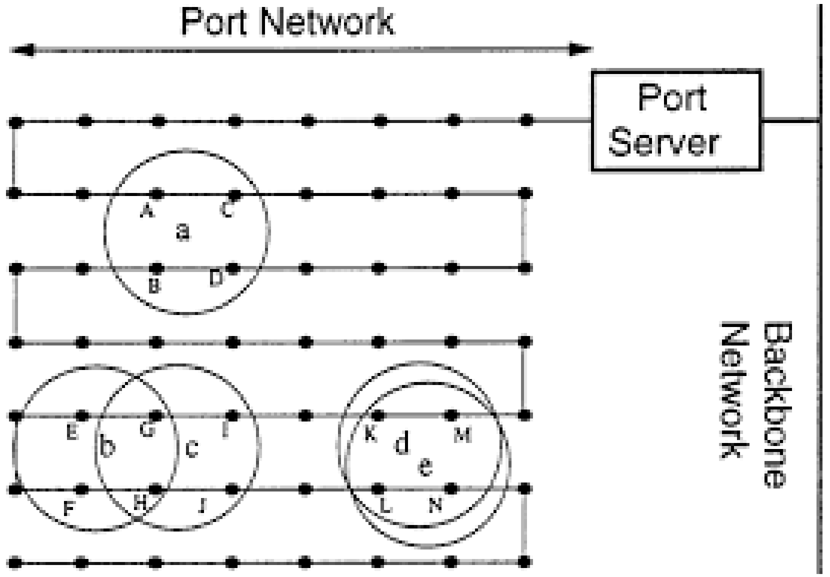
and

- **We raise the CCA threshold**

Max Riegel, Nokia, Munich, in EU Horizon 20202 ELIoT

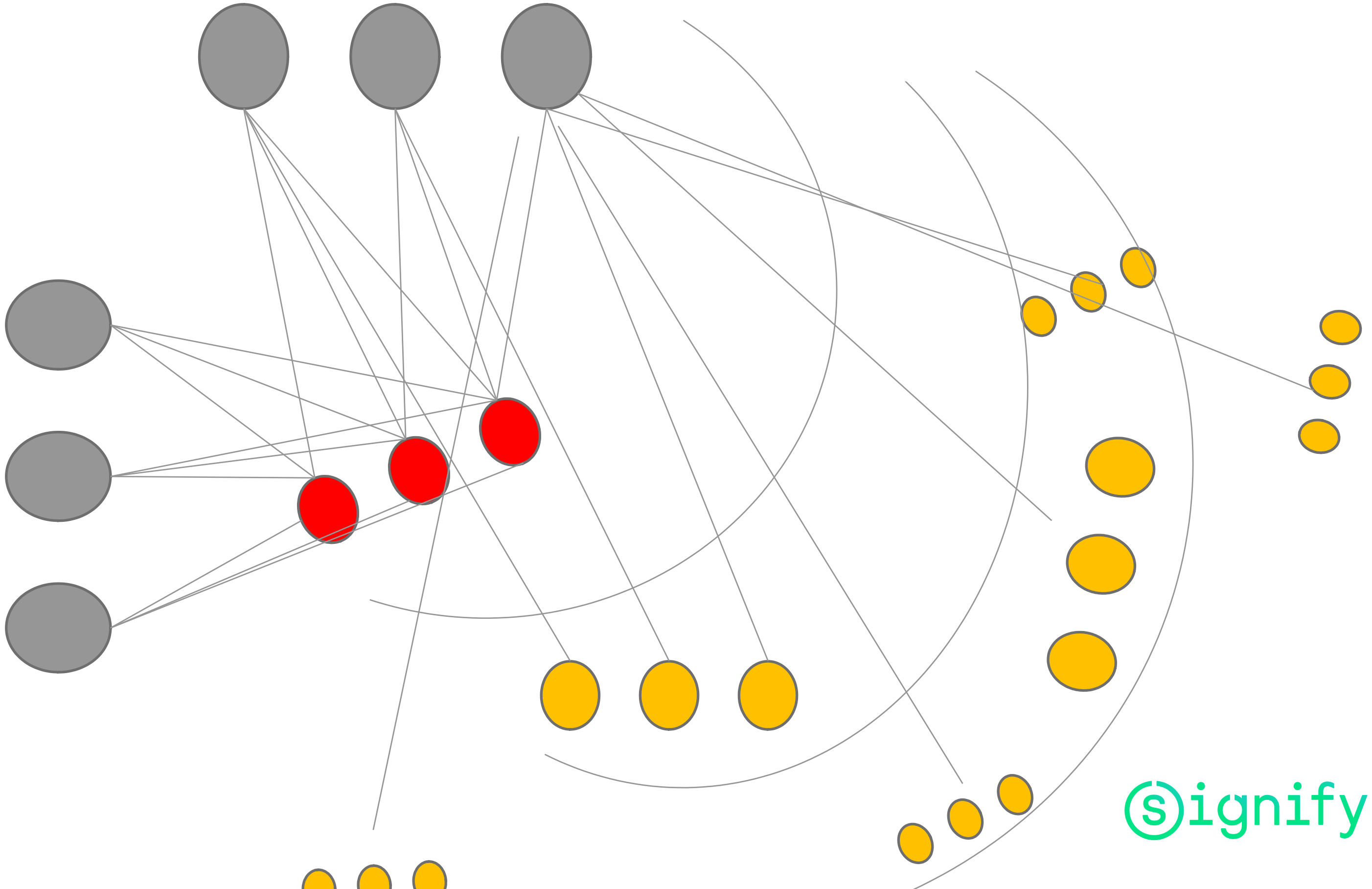


Do more APs help?
Does Massive MIMO and beam steering help?



But Access point can help each other
Virtual cellular network: a new wireless communications architecture with multiple access ports. Vehicular Technology Conference, 1994 IEEE 44th

Just bringing in more access points may not help:
- the number of degrees of freedom (number of TX antenna's) is not adequate to actively null interference
- At larger ranges, a collection of MIMO APs just looks like an increased noise floor



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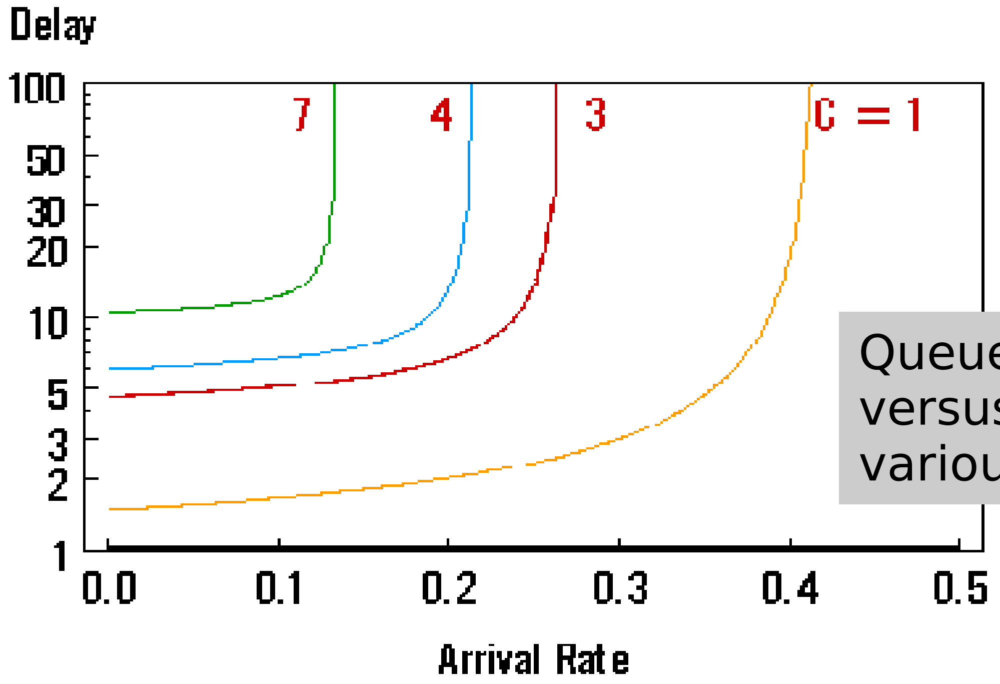
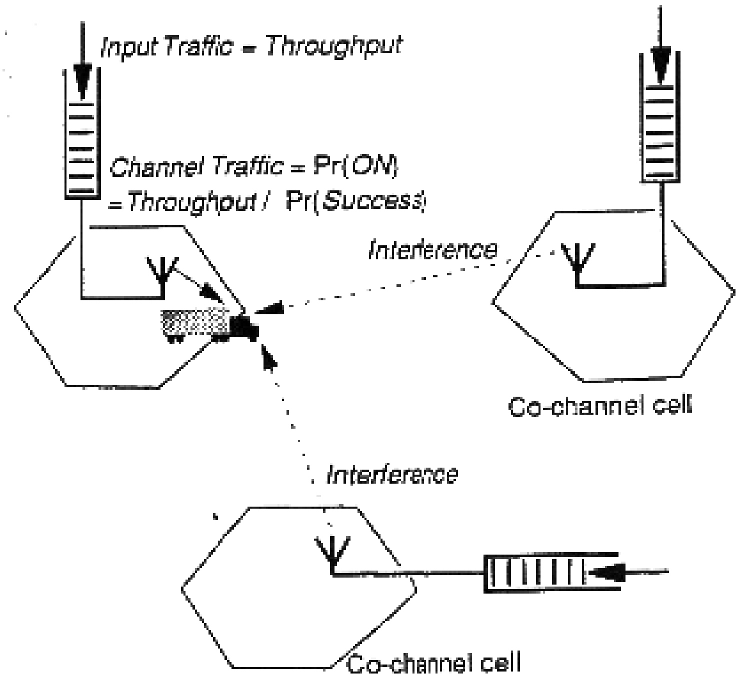
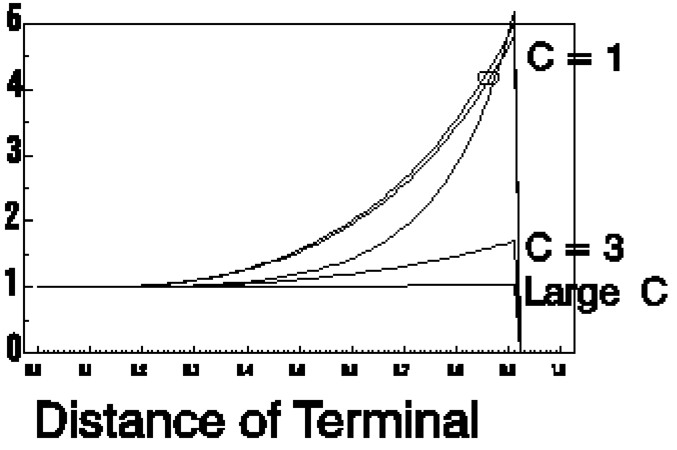
Splitting bandwidth is not a good idea
in packet traffic

Splitting bandwidth increases the transmit time per cell and lengthens the queue



Queueing delay versus arrival rate for various cluster sizes.





Linnartz, JP.M.G. On the performance of packet-switched cellular networks for wireless data communications. *Wireless Netw* **1,** 129–138 (1995). https://doi.org/10.1007/BF01202536

SNR vs MCS/PHY rate

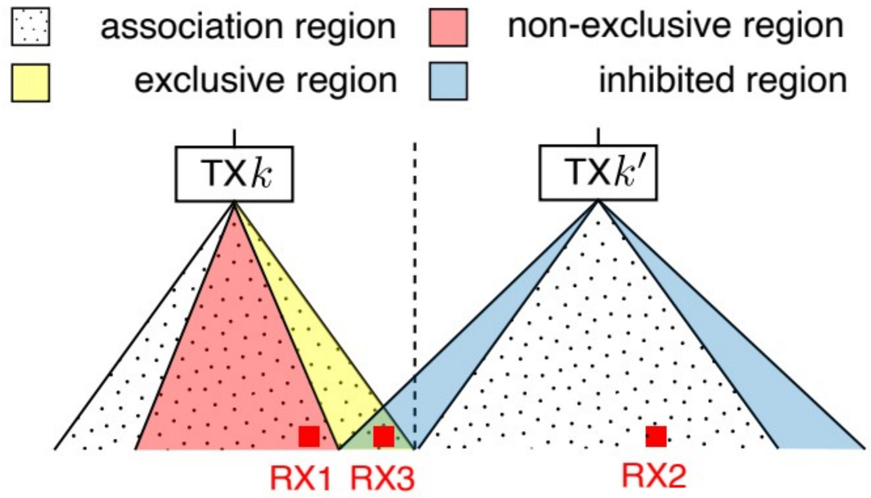
TABLE II. MCS(SINR) AND USER RATE(SINR) FOR PER = 0.01 USING FADING TGAX CHANNEL MODEL 'B' – SIMULATION RESULTS

SINR / dB	MCS	User Rate / Mb/s	PHY Rate / Mb/s
17	0	8	8.6
19	1	15	17.2
23	2	22	25.8
25	3	26	34.4
29	4	36	51.6
32	5	45	68.8
34	6	47	77.4
36	7	48	86.0
39	8	56	103.2
41	9	57	114.7
44	10	62	129.0
46	11	63	143.4

Reusing the channel in the same building reduces the C/I

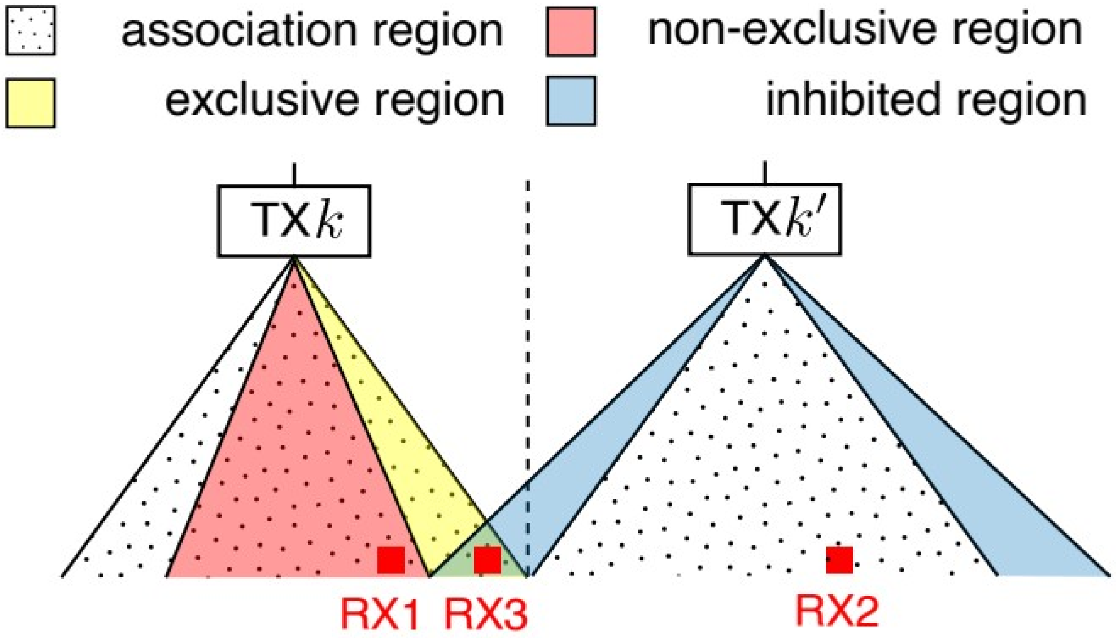
This reduces the achievable bit rate

Is it better to use the channel once at good C/I
Or
To use it twice at low C/I thus low throughput



TDMA Scheduling in Spatially Extended LiFi networks

Jona Beysens, *Student Member, IEEE,* Jean-Paul M.G. Linnartz, *Fellow, IEEE,*
Dries Van Wageningen, Sofie Pollin, *Member, IEEE*



The cross-over point is, on a log scale, located where the interference term is exactly in the middle of the signal term and the noise term. As capacity expressions also take a logarithm of signal-to-noise ratios, this implies that half the ideal interference-free capacity can be achieved. The same rate can be obtained when time-sharing with two TXs. If the interference term is smaller than this midpoint, then it is better to allow interference. If the interference term is larger than this middle point, then it is better to avoid interference.

IEEE Open Journal of the Communications Society, 2020

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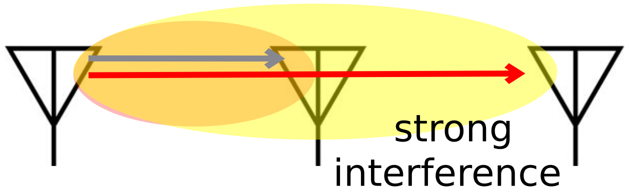
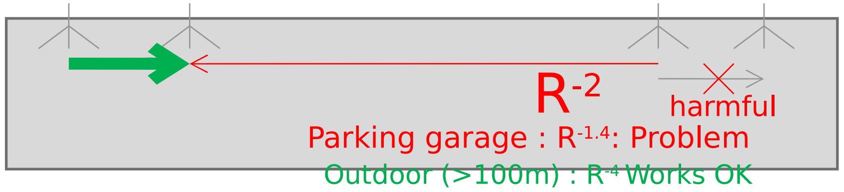
Essential difference No. 1:

Spectrum Reuse and Scalability

Radio (ZLL, …) links



There is a direct link between Tx and Rx
Walls are transparent



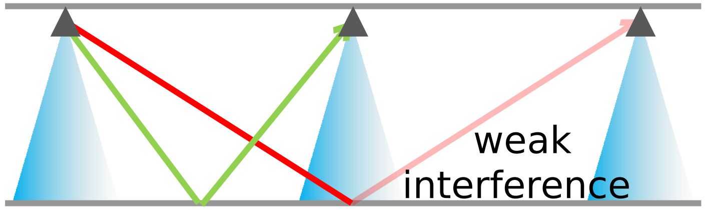
Each node sees (too) many other nodes

Interference: also more remote tiers of interferers contribute

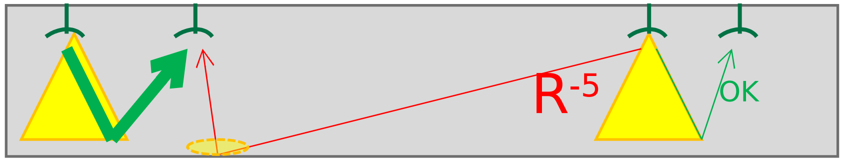
Total interference diverges

So, Radio has a fundamental problem in being not scalable in “free space” environments (large halls, parking garages)

Optical Light wave (IR, VLC, CL) Link



There is NO direct link between Tx and Rx. Walls are opaque leading to confinement. Reflection coefficients 0.4-0.7



Each Luminaire sees (the light footprint) of (only) a limited number of other Luminaires:

reuse of communication spectrum is possible

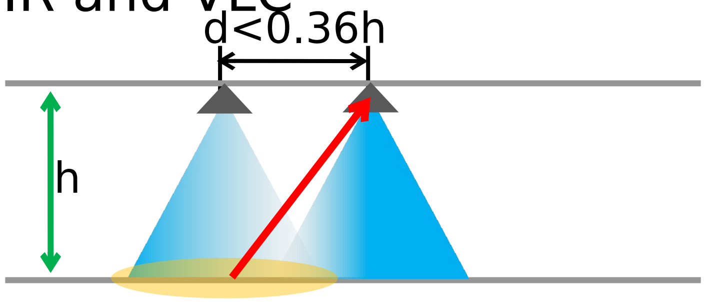
Different Mechanisms of Propagation for IR and VLC

Short Range

Complete reflection for small distances

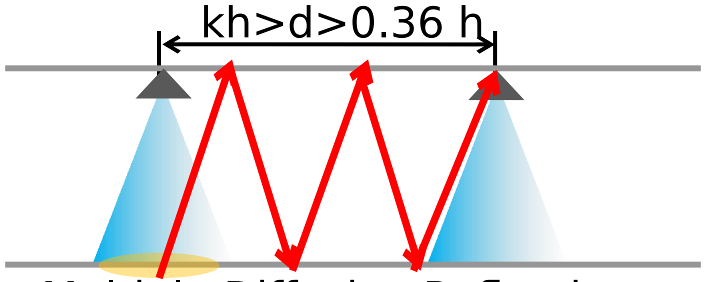
Most of the power emitted by the LED could be considered to look at the detector with a specific angle cosθ≈1θ<20deg and:

θ ↓ for n>1 (lambertian order) of the Rx



Multiple Reflections for LEDs at moderate distances

This is the most difficult region
it spans from ~0.36 h to a few multiples h



Multiple Diffusive Reflections

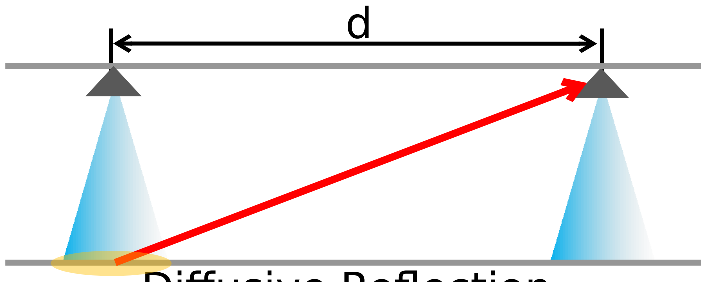
Long Range

Diffusive Reflection (also the symmetric one)

Only the regions below Tx and Rx contribute

in the amount of the received power :

m and n the lambertian orders of Rx and Tx

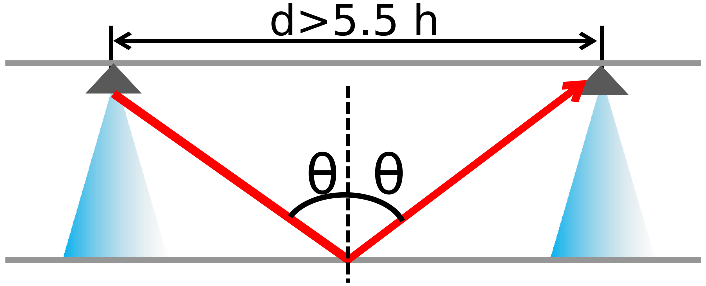


Diffusive Reflection

Specular Reflection for distances d>5.5 h (θ>70deg)

For very swallow angles (θ>70deg) the floor and
the walls start supporting specular reflection (diagram in the last page):

m and n the lambertian orders of Rx and Tx



Snell's Law Applies

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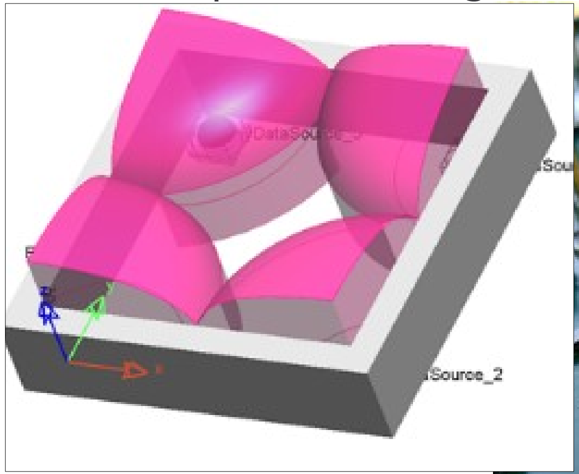
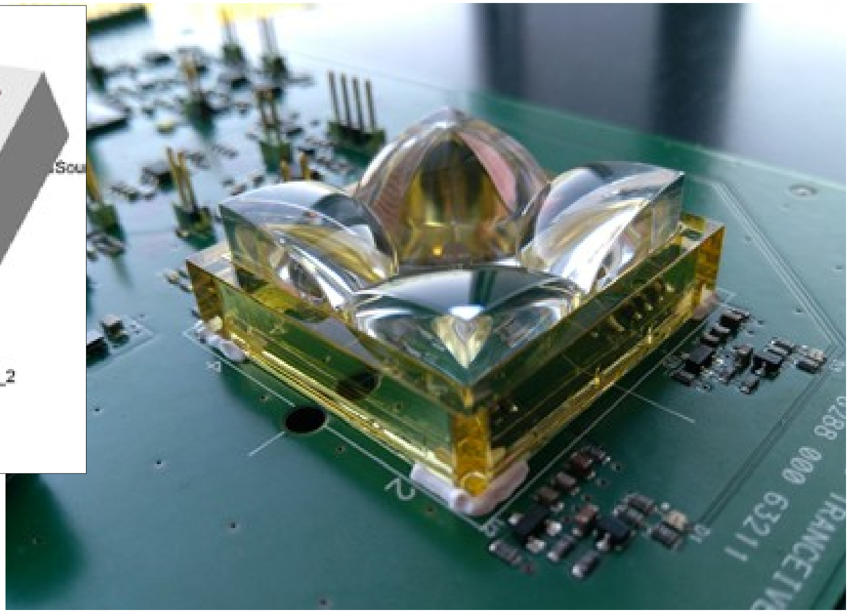
Design of a sectorized LiFi system

SPIE PW22-12022-48 Linnartz et al.

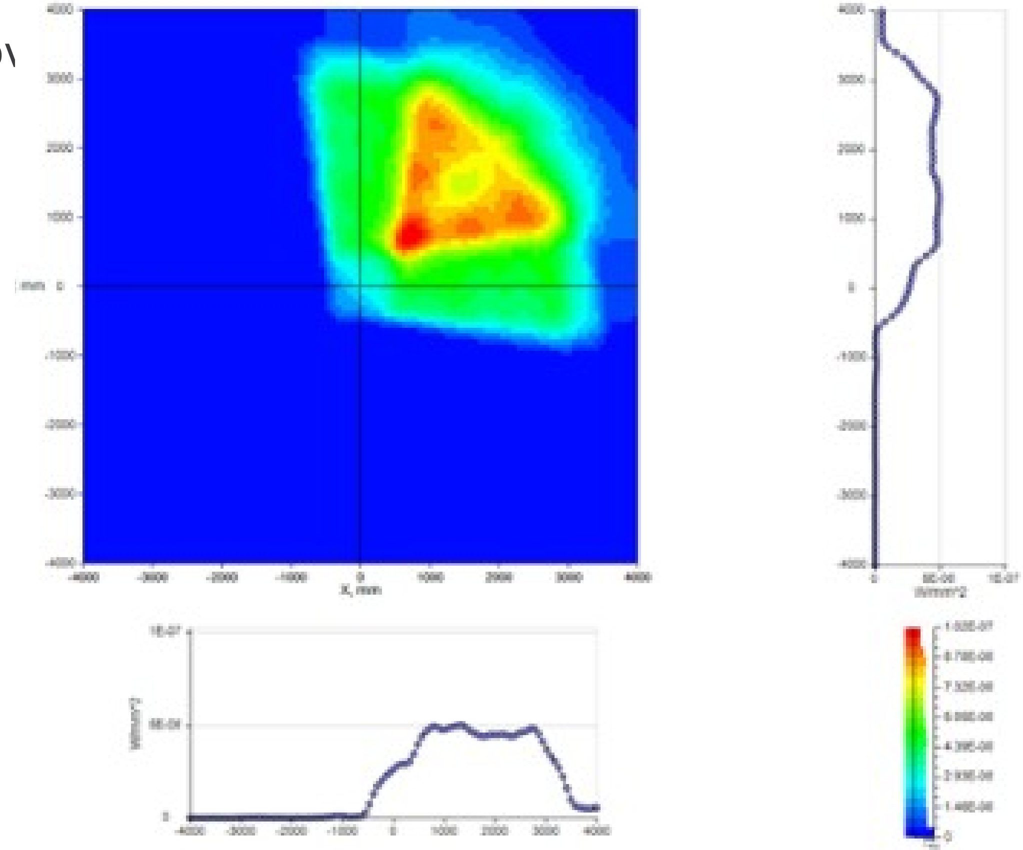
- Reference emitter replaced by 4 emitters with each ¼ of the reference chip area
- Lens replaced by free-form optics to irradiate 4 segment areas with flat irradiance profile and some limited overlap
- Design principles:
  - Segmentation gain in performance used to increase the cov area rather than the on-axis data rate for equal TX power
  - Unchanged max throughput re the reference
  - Flat profile with gradual decrease at the cell boundaries



Design of 4-sector emitter with free-form lens



Sample of 4-sector emitter with free-form lens



Modeled irradiance in target plane by a single sector emitter

Linnartz JP, van Voorthuisen P, Hoelen C. Enhancing indoor optical wireless communication system performance by sectorization. In Light-Emitting Devices, Materials, and Applications XXVI 2022 Mar 3 (Vol. 12022, pp. 78-96). SPIE.

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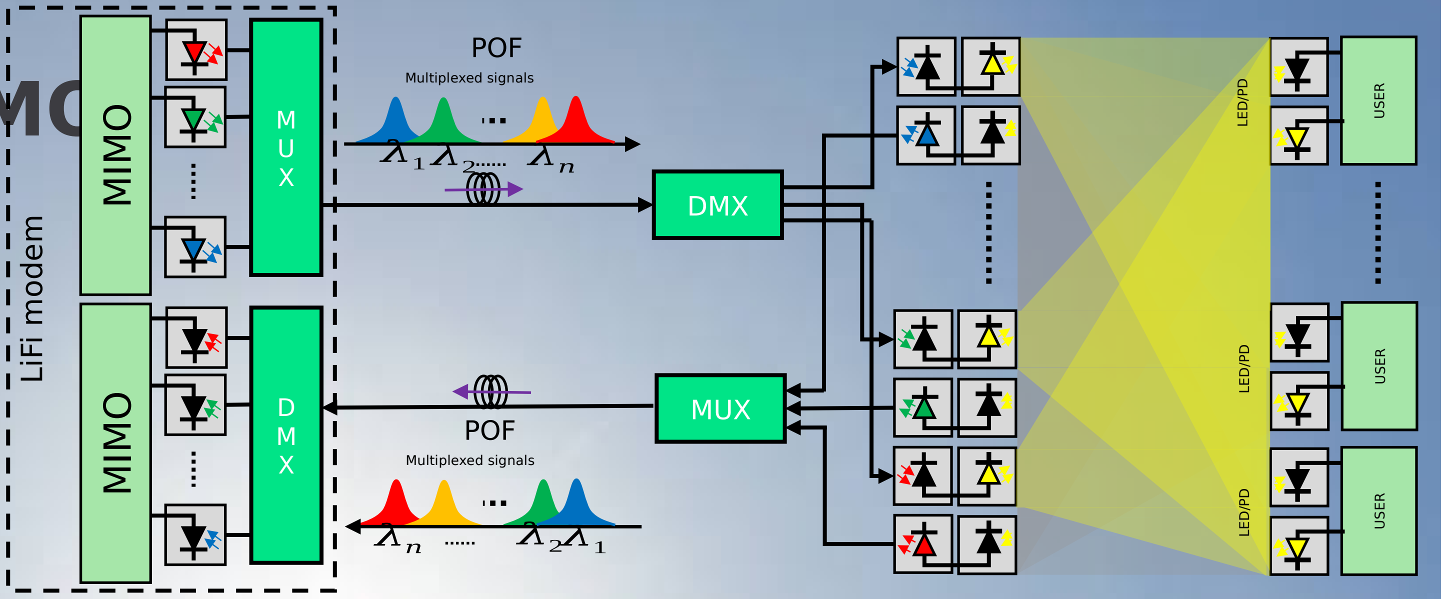
Distributed MIMO



Spatially separated ceiling OFEs

Directionally sensitive client OFEs

Statistical model: accidental blocking a LoS

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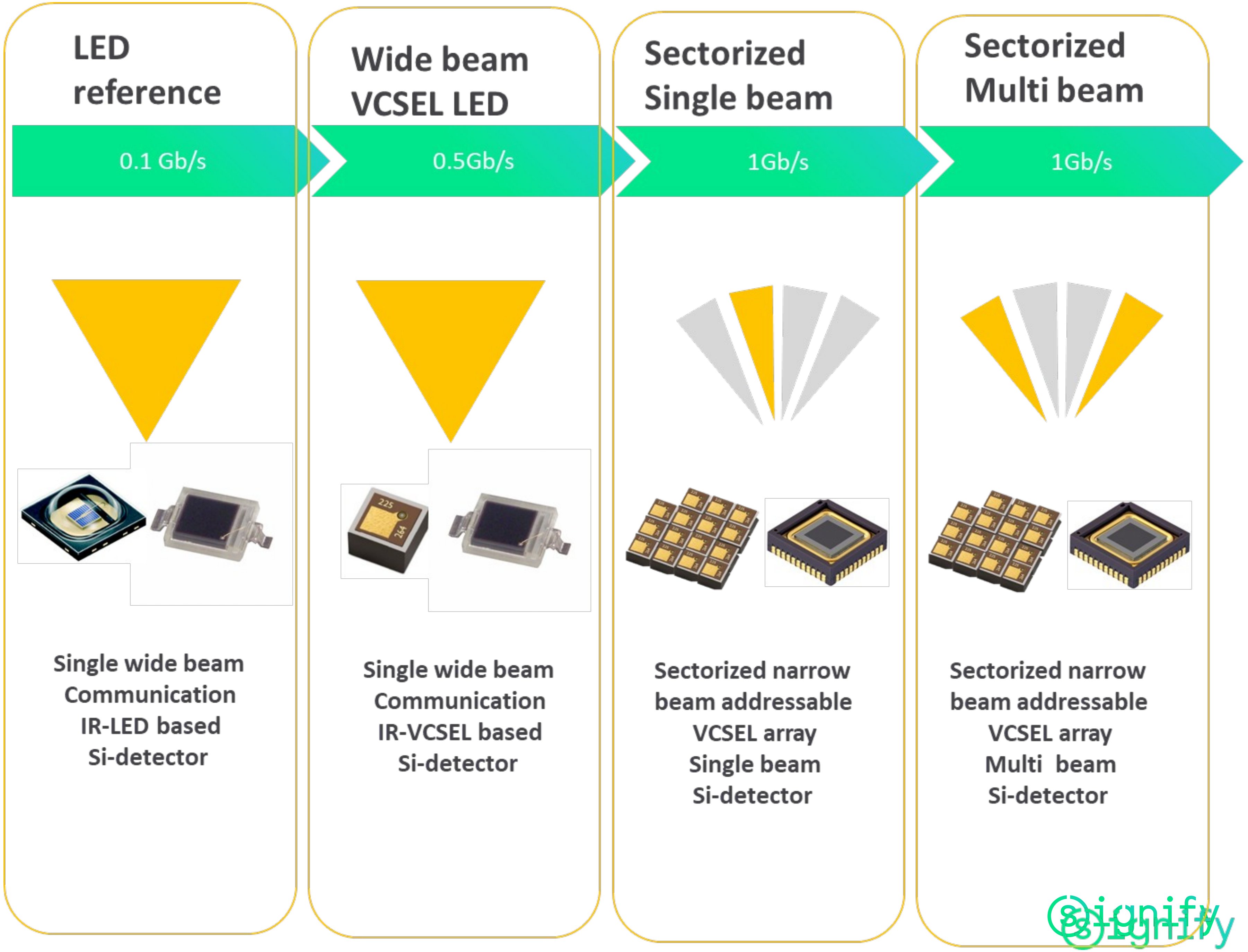
VCSEL array

- Array of individually addressable VCSEL (16 or 256) of the same wavelength
- Optics to give all VCSEL elements its own cell footprint with adequate SNR



Photonic Integration to enable our vision

Narrower beams as leading innovation theme:

- Higher bitrates (more power at the receiver)
- more users per room by reduction of interference
- Size and power reduction
- Integration into the smartphone

Photonic Integration is a must:

- To enable narrow beams
- Cost reduction
- Size reduction (e.g. in

GaAs / Si

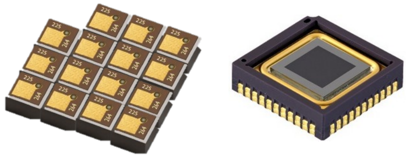
0.1 Gb/s

Single wide beam Communication
IR-LED based
Si-detector
Discrete optics
Non-integrated

Signify's current products

GaAs / Si / InP

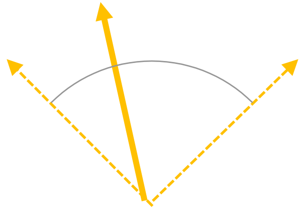
1Gb/s

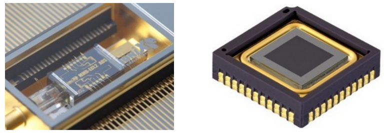


Multi beam 10-100
VCSEL array 800-1000nm
Integrated array driver
Multi segment
Si-based integrated photonic IC
Module level integration of optics

InP

10Gb/s

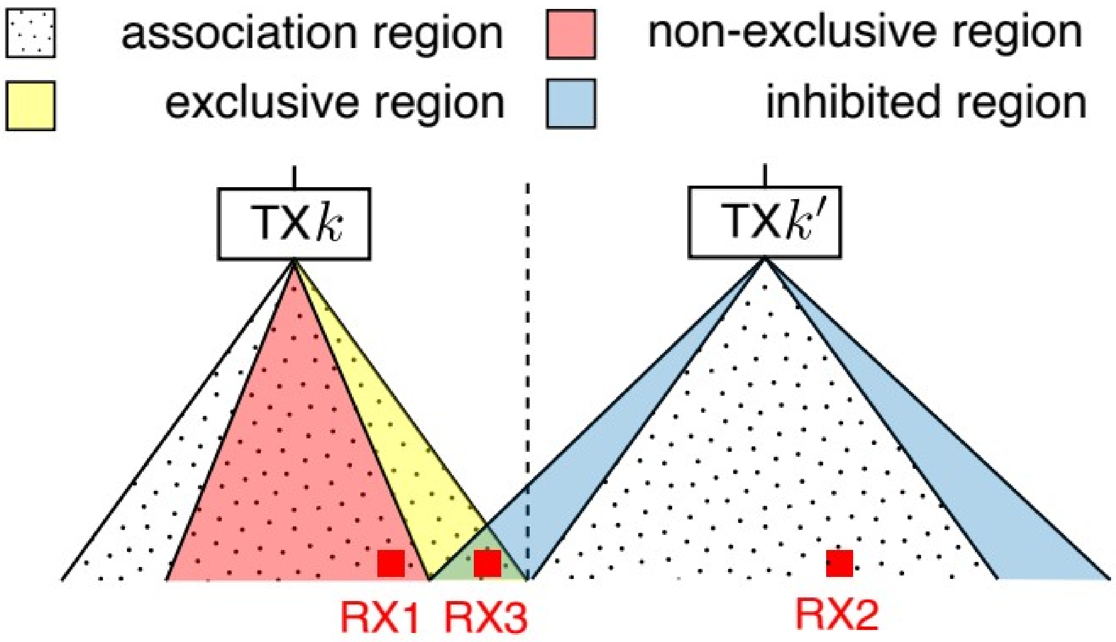




Steerable narrow beam
1300-1500nm
Module Integrated array driver
Multi segment
InP-based segmented detector
integrated photonic IC
Module level integration of optics

Eco system

Conclusions



RF networks may not scale to further reduce cell sizes

Do not only consider the nearest interferer in your analyses

Interference from other light emitters does not accumulate as dramatically as with RF

LiFi Networks scale much better to serve very dense areas

I am seeing a renewed interest in some of my early research results.

- Scalability
- Spatial multiple-access
- Virtual cells

signify