IEEE COMSOC LATIN AMERICA OPEN WEBINAR

Optical Wireless Technologies: Opportunities and Challenges in 5G+

Team Finland Knowledge (TFK) program

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6G and Digitalization at Aalto University

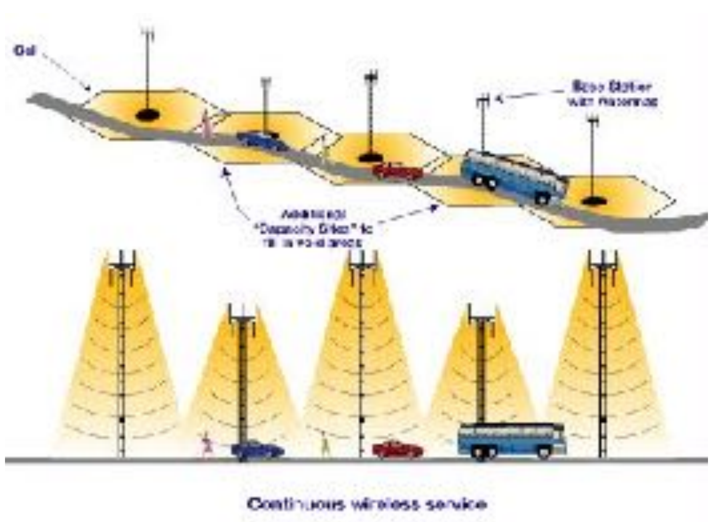
- Aalto University has 80+ Profs. in core ICT disciplines, distributed in many departments: • Antenna & RF tech.;
  • Fundamentals of Information and Communication Eng.;
  • Communications and Networked systems;
  • Human-centric technologies, among others
- Some research directions for 5G+

— Sustainable ICT (Green transformation)
— Human-centric AI and intelligent systems
— AI-enabled networking
— Softwarization and cloudification
— Cyber and network security
— Joint communications and sensing
— Quantum communications

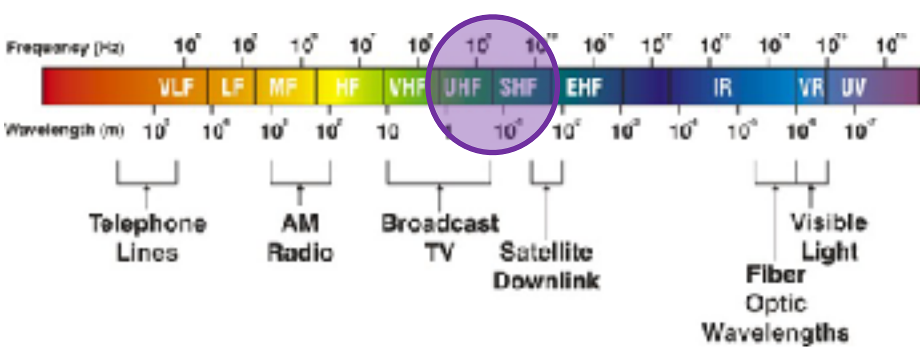
To understand the role of Optical Wireless Communications (OWC) technology beyond 5G, we first need to define:

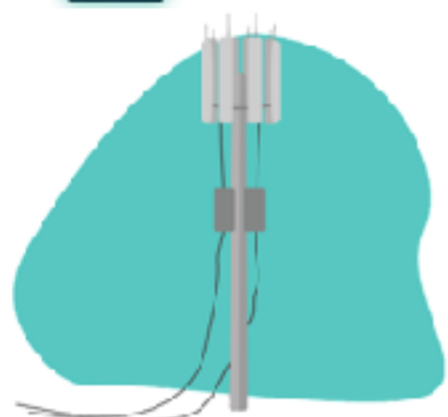
What is 5G?

Mobile network – Cellular concept



Mobile Communications (RF)





Cellular structure like honeycomb

Source: *6g.mooc.fi*

Mobile network – From 1G to 5G

- The last 40 years, the world has witnessed five mobile generations

Foundation of mobile telephony	Mobile telephony for everybody	Foundation of mobile broadband	Further enhanced mobile broadband	Interconnected devices sensors and systems (verticals)
1G	2G	3G	4G	5G
AMPS TACS NMT	GSM D-AMPS PDC IS-95	WCDMA/HSPA cdma2000	LTE	NR
1980s	1990s	2000s	2010s	2020s

The different generations of mobile communications

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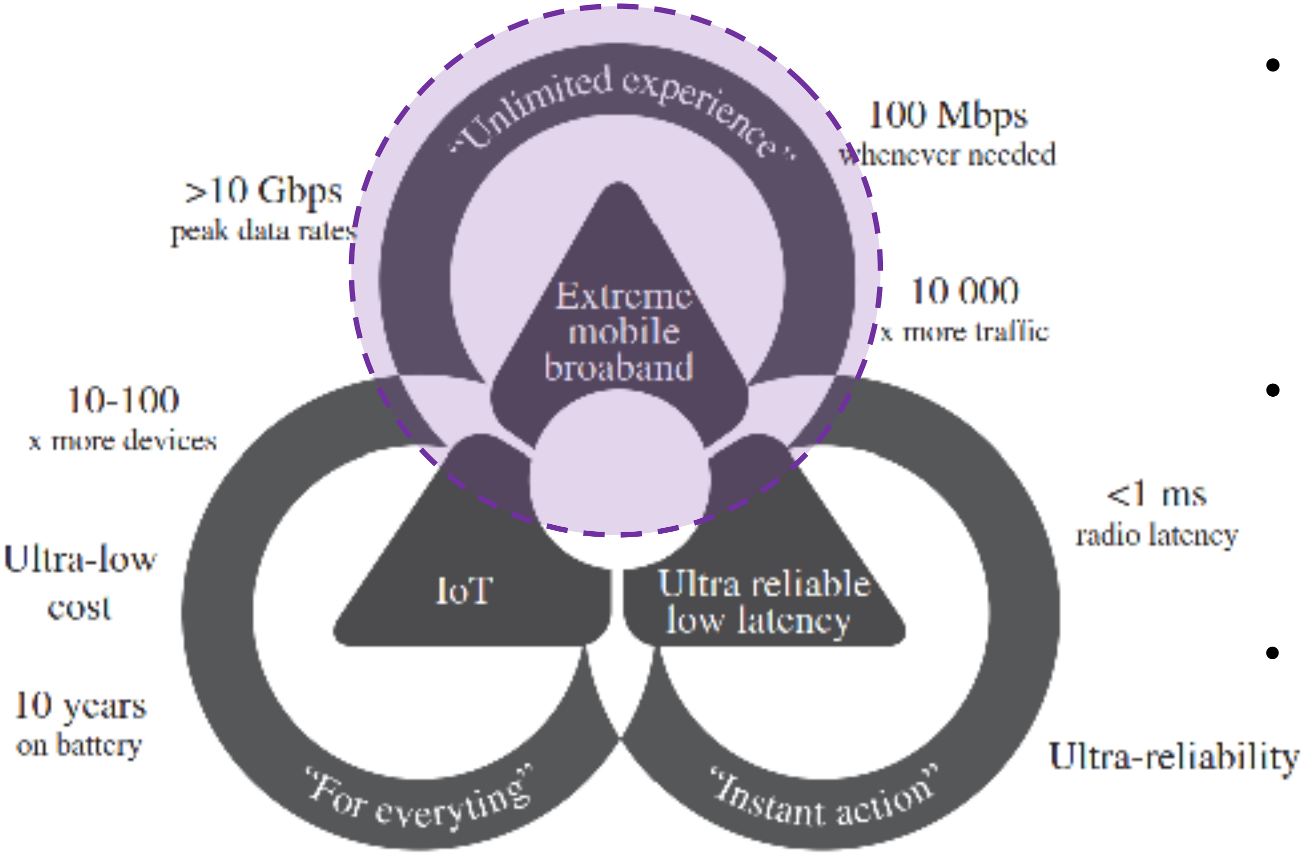
What is 5G? – 5G targets



- **Extreme mobile broadband (eMBB):** Take traditional mobile broadband to the extreme (smartphones)
- **IoT:** Relevant for massive machine-type connectivity, such as in industrial environments
- **Ultra reliable low latency communications (URLLC):** Relevant for industrial automation and similar services

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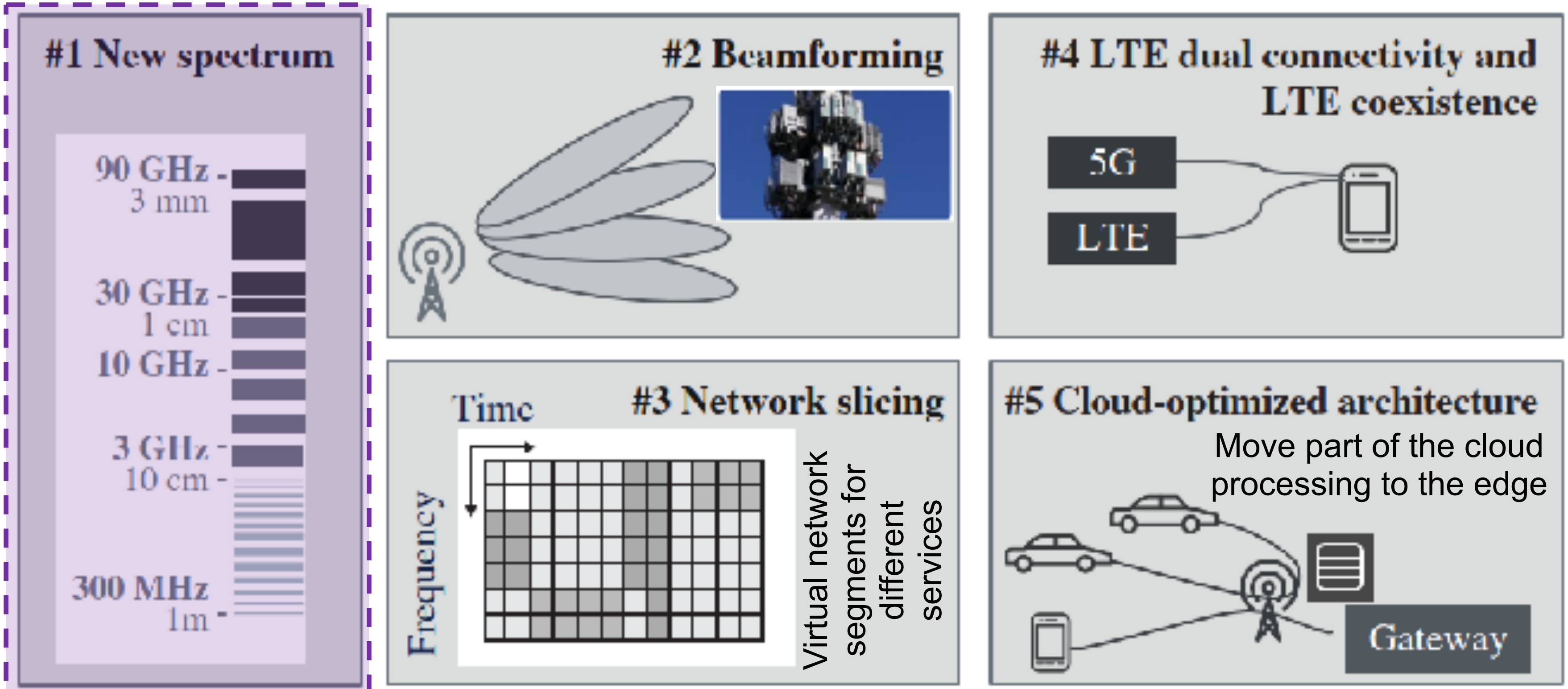
Source: 5G technology – 3GPP New Radio

What is 5G? – Technology components

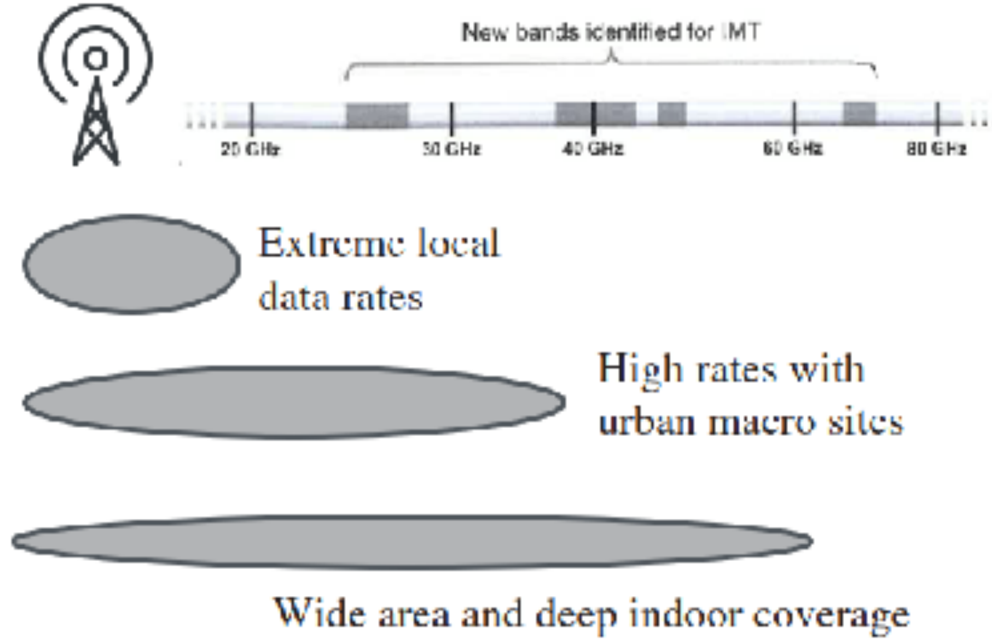


Source: 5G technology – 3GPP New Radio

What is 5G? – 5G Spectrum

New bands identified for IMT (WRC-19)

Spectrum	5G spectrum per operator	Data rate
20–90 GHz	1 GHz	5–20 Gbps
Below 6 GHz	100 MHz	2 Gbps
Below 1 GHz	10 MHz	0.2 Gbps

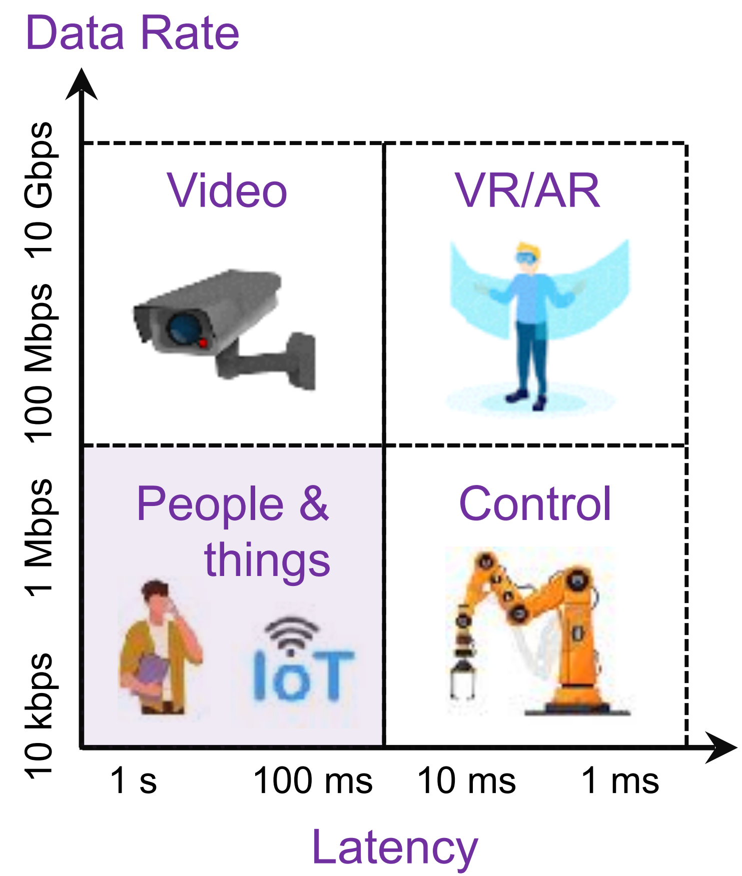


- 5G NR is designed for flexible utilization of all available spectrum resources from 400 MHz to 90 GHz, including licensed, shared, and unlicensed (TDD/FDD)

What is 5G? – 5G use cases

5G enables new use cases for consumers, enterprises, home, and public domain:

- **Higher capacity:** 360-deg viewing videos, especially in mass events
- **Virtual reality (VR)/augmented reality (AR):** Gaming and similar use cases
- **Remote control and machinery:** High-data rate, low latency and extreme reliability in industrial applications
- **People and things:** Public safety, agriculture, health care monitoring, fixed wireless access to homes and SMEs



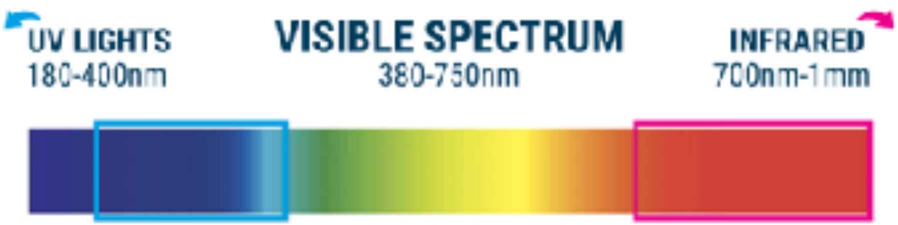
Now that we more about 5G, which is mainly based on radio signals,

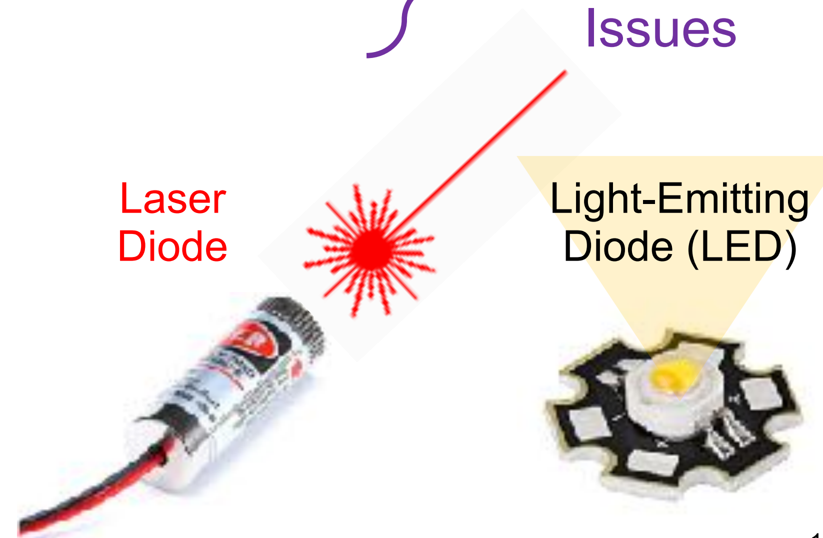
What is Optical Wireless?

Optical Wireless – About terminology

- **Optical Wireless Communication (OWC)** refer to the transmission of information on an unguided propagation media using optical carriers
  - — Visible Light → Transmitter (TX) is typically an LED
  - — Infrared (IR) → Mostly Laser (but also LED)
  - — Ultraviolet (UV) → LED, *etc.*

Possible Health-related Issues





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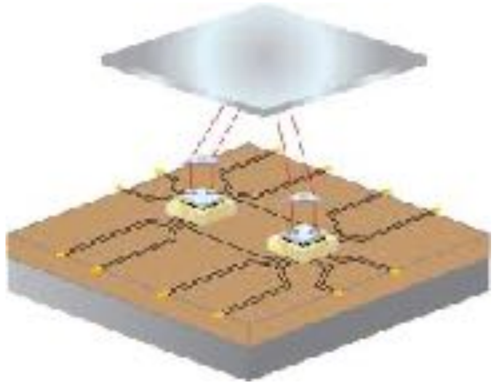
Optical Wireless – About terminology

- **Free Space Optical (FSO)** typically refers to outdoor terrestrial optical wireless links that provide long-range point-to-point connectivity in IR bands (the transmitter is usually a laser)

IR = Infra-Red; VL = Visible Light

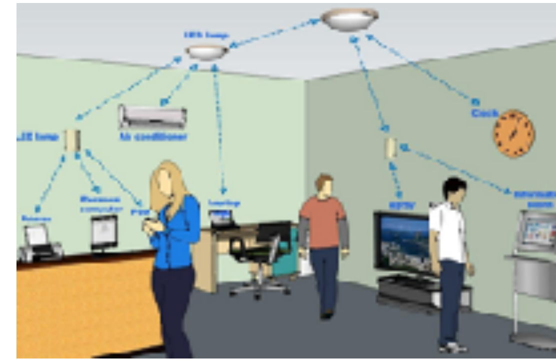
- **Visible Light Communication (VLC)** is typically used to refer indoor OWC systems that provide illumination and data services simultaneously over VL bands (the transmitter is usually an LED)

OWC classification – According to range



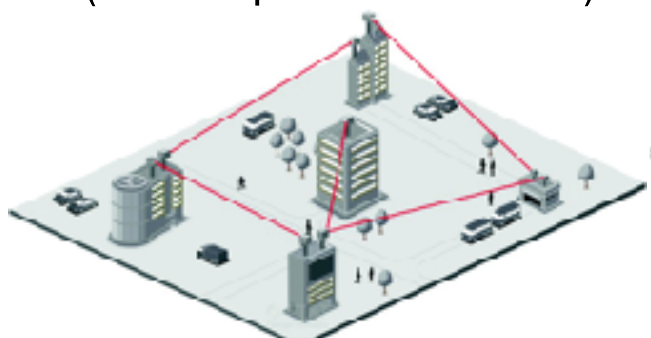
Ultra-shot range
(intra-chip communication)

Ultra-short range
(inter-chip communication)

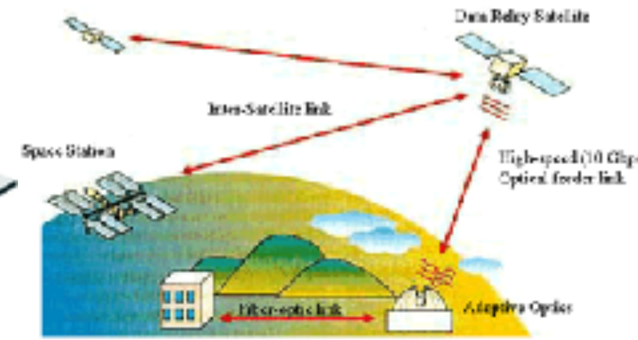


Short range
(same room communication)

Medium range
(vehicle-to-vehicle)



Long range
(inter-building communication)



Ultra-long range
(Inter-satellite links)

Visible Light Communications

… and its suitability to provide wireless access beyond 5G

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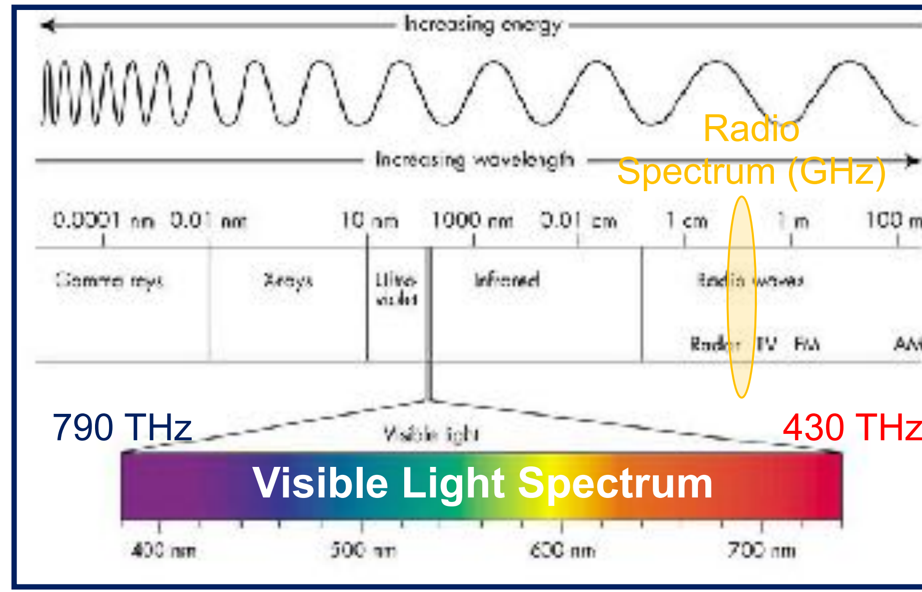
VLC technology – Advantages of its use

- Much more spectral resources than in RF
- License-free EM spectrum
- VLC signal is blocked by obstacles (better security)
- Compatible with ultra-dense deployments (interference)
- Reuse of light infrastructure (energy) for communication
- Avoid Electromagnetic Compatibility (EMC) problems



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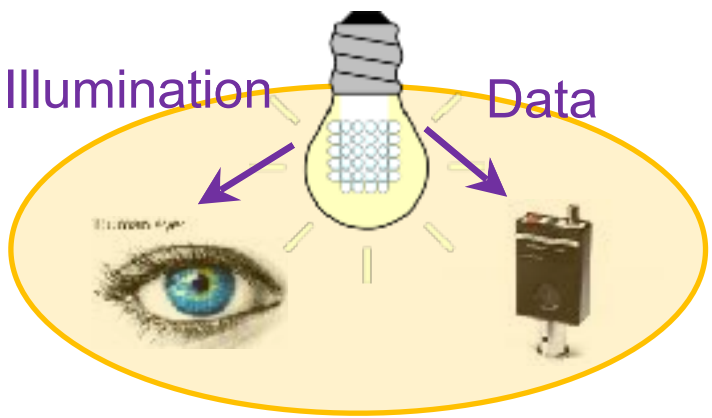
VLC technology – Main concept

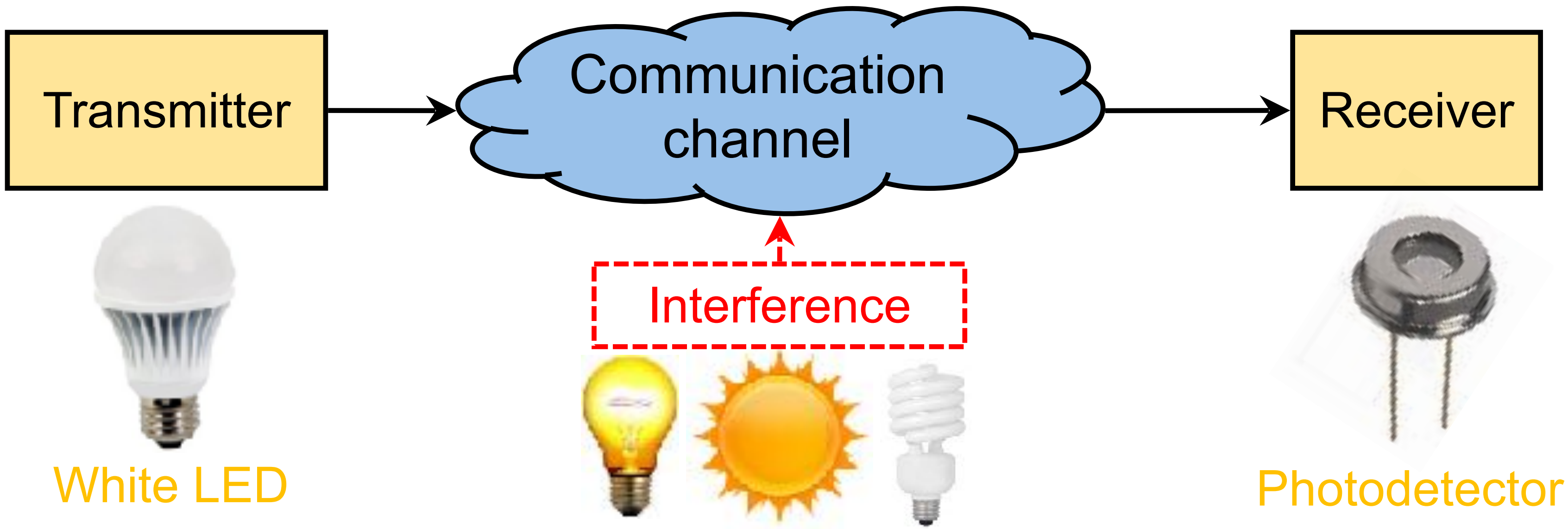
- Current incandescent and fluorescent lamps are replaced by LED lamps
- LEDs can switch their light intensity level at a very fast rate

- This switching rate is fast and is imperceptible for humans



- A photodetector can receive the modulated signal and decode the data
- This mean that the LED can serve for a dual purpose: Provide *illumination* and *communication* at the same time

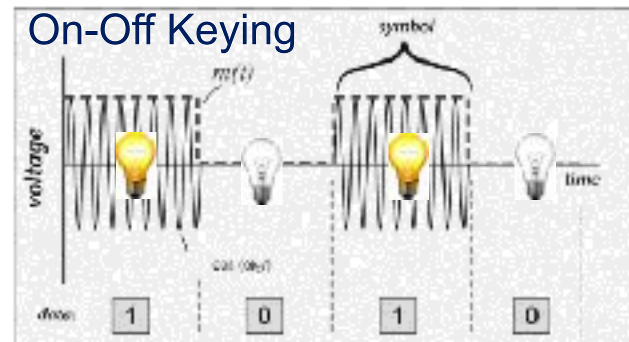
VLC system – Simplified block diagram



- Focus: Use of visible light for communication indoors
- **Components of a VLC system:** Transmitter, receiver, and visible light communication wireless channel

VLC system – Modulation schemes

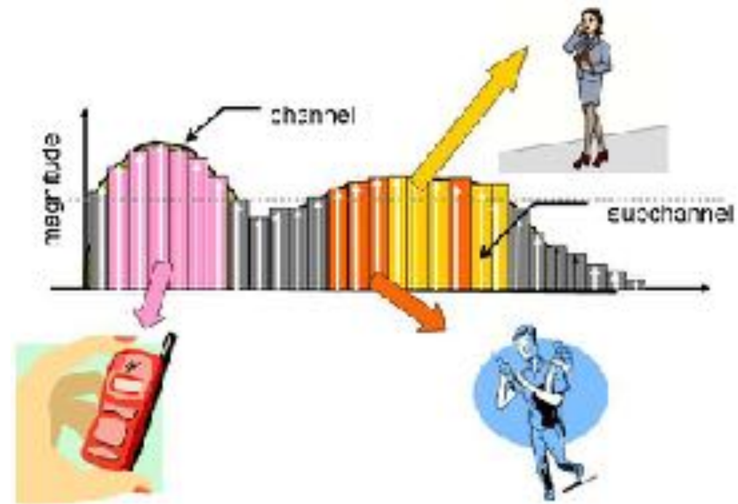
- Visible Light Communication is implemented in practice as an Intensity Modulation (IM) Direct Detection (DD) system
- Only signal intensity can be detected reliably and, without modification, only few RF digital modulations can be used
- Unipolar modulation schemes:
  - On-Off Keying (OOK)
  - Pulse Position Modulation (PPM)
  - Pulse Amplitude Modulation (M-PAM)



- However, unwanted Inter-Symbol Interference (ISI) appears as the transmission data rate increases
  - Hence, more resilient techniques are preferred (*e.g.*, OFDM-based)

VLC system – Complex baseband OFDM

- Orthogonal Frequency Division Multiplexing (OFDM) allows equalization to be performed with a single-tap equalizer in the frequency domain (lower design complexity and cost)
- Different sub-carriers can also be adaptively loaded if information corresponding to the channel characteristics is available
- This enables a better usage of the usage in case of strong attenuation or interference in certain bands

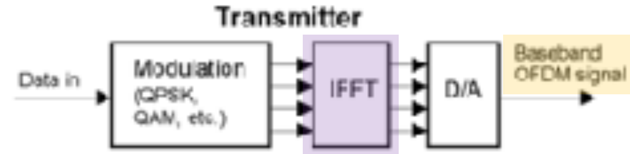


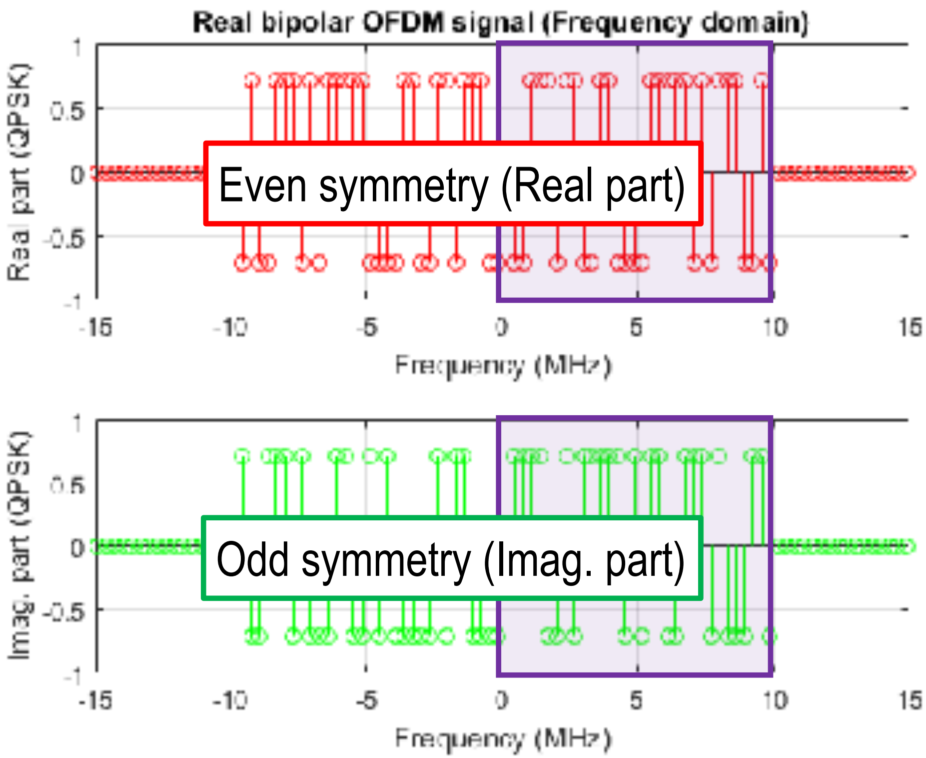
- However, conventional OFDM signals are bipolar and complex valued (*i.e.*, they are not suitable for IM systems)

VLC system – Real-valued baseband OFDM

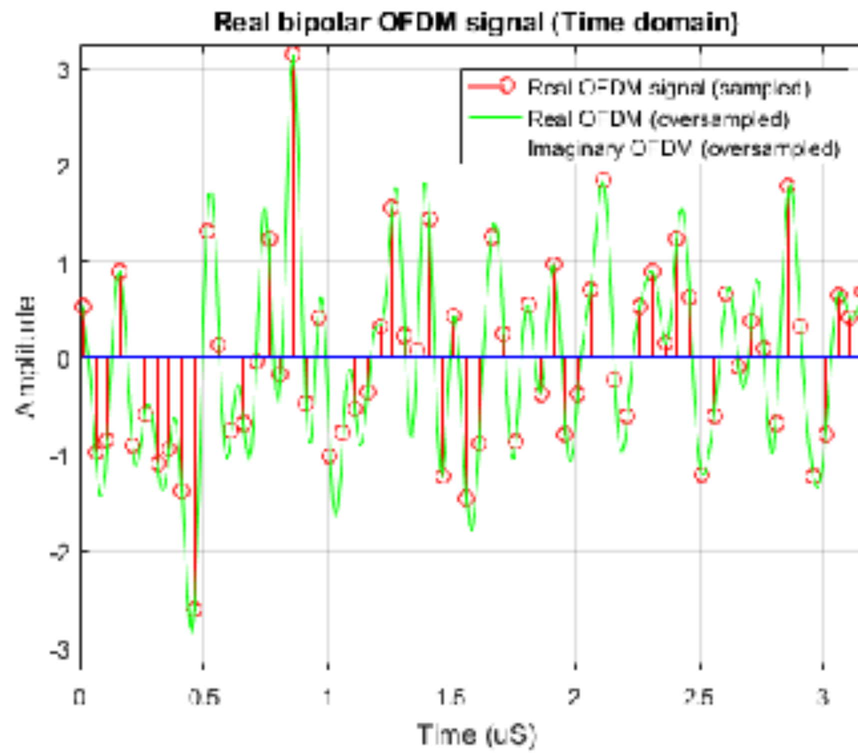
- Optical OFDM schemes are modifications of conventional OFDM that fulfill the requirements of IM systems
- An OFDM signal can be transformed into a real signal by imposing Hermitian Symmetry on the frequency subcarriers
- Furthermore, different approaches have been proposed to deal with the issue of bipolarity of the OFDM signal:
  - **DCO-OFDM:** Direct-Current-biased Optical OFDM
  - **ACO-OFDM:** Asymmetrically Clipped Optical OFDM
  - **PAM-DMT:** Pulse-Amplitude-Modulated Discrete Multi-tone
  - **U-OFDM:** Unipolar OFDM (also known as Flip-OFDM)

VLC system – DCO-OFDM



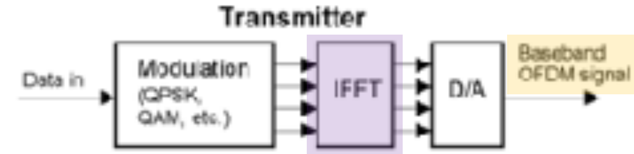


OFDM frequency-domain signal (Hermitian symmetry is verified)

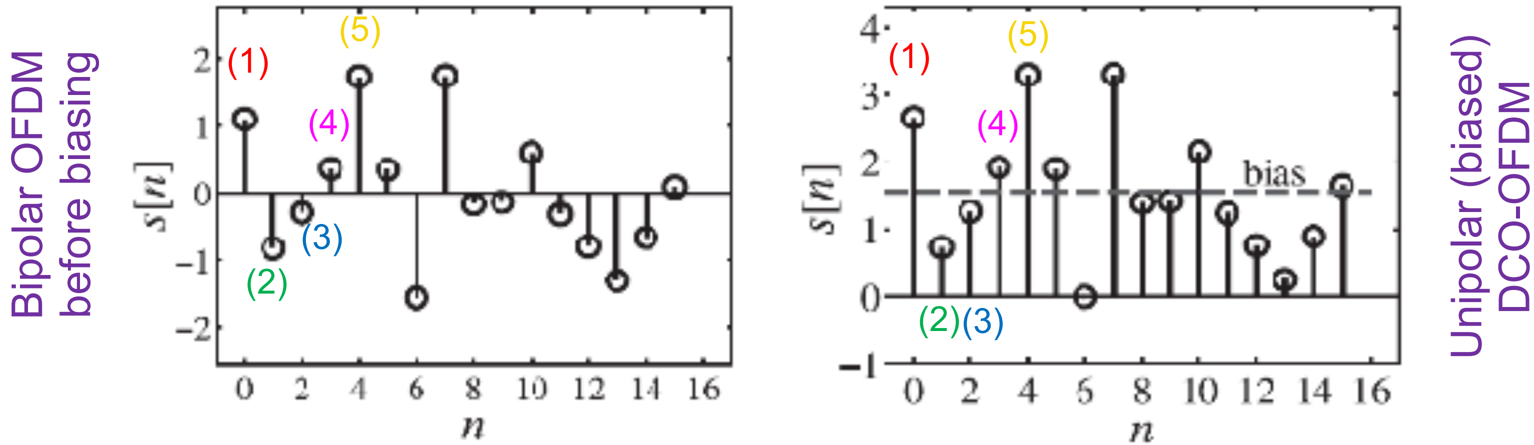


OFDM time-domain signal before DC-offset (Imag. part always null)

VLC system – DCO-OFDM



- DCO-OFDM generates a unipolar signal introducing a DC bias



- OFDM has a very high Peak-to-Average Power Ratio (PAPR)
- Therefore, it is impractical to introduce a biasing level which ensures all possible time samples to be positive
- Moreover, OFDM signal will be clipped from above and below (max-min operational range), creating non-desired distortion

Light Communications – Standardization

- **G.9991 (G.vlc)** recommendation of ITU for *"High speed indoor visible light communication transceiver"*
- **IEEE 802.11bb** amendment on IEEE 802.11 standard
- **IEEE 802.15.7-2018** and **IEEE 802.15.7-2011** standards for short-range OWC and VLC (multimedia)
- **IEEE 802.15.13** standard for multi-Gigabit/s OWC (point-to-point and point-to-multipoint)

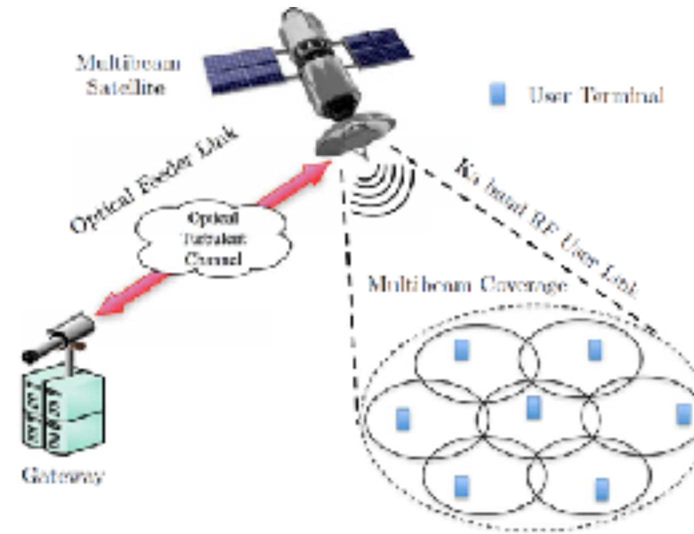
IEEE 802.11™ IEEE 802.15 ITU Standardization Sector ITU-T

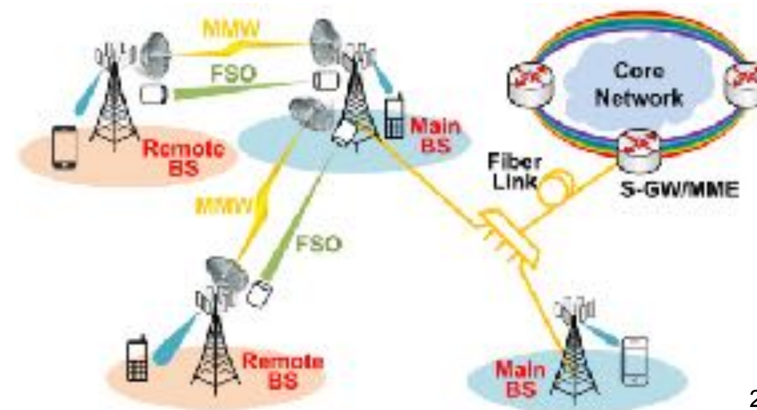
Free Space Optical

… and its suitability to provide point-to-point wireless backhauling beyond 5G

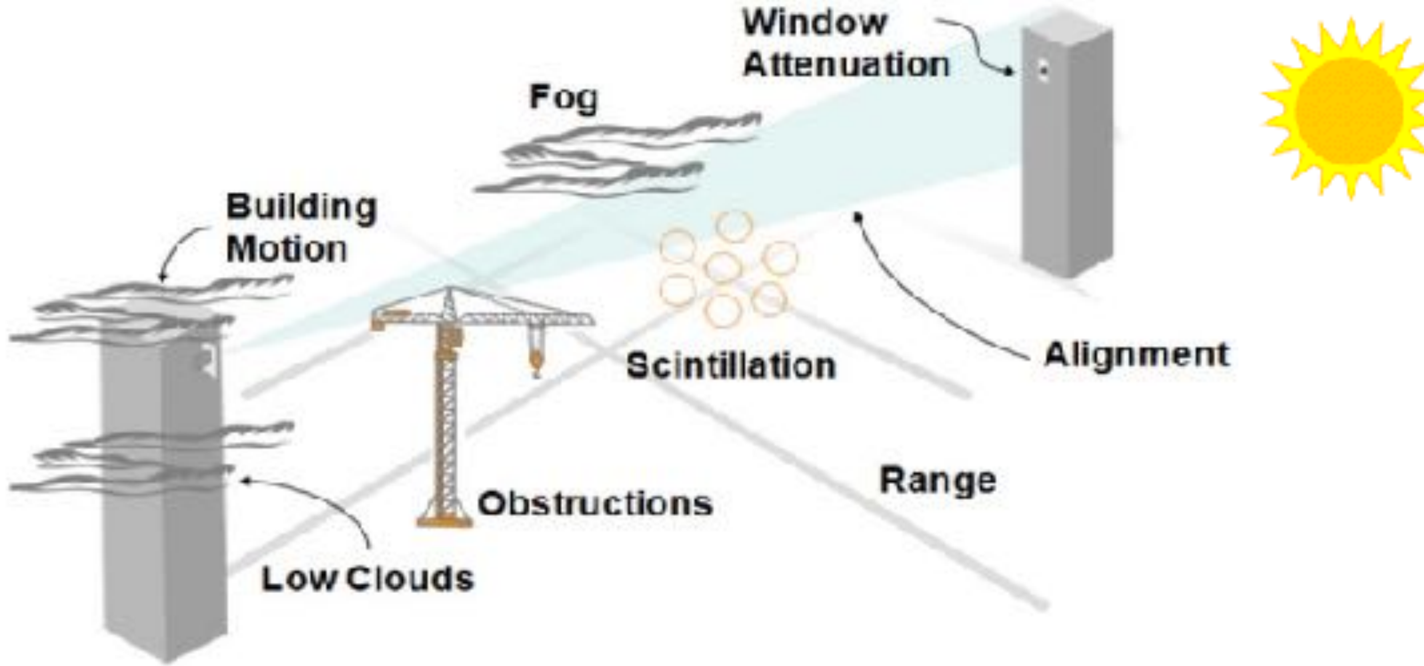
FSO technology – Applications

- MAN extension and LAN-to-LAN connectivity (backhaul links)
- Optical fiber back-up links and backhaul for cellular networks
- Disaster recovery (temporary links)
- Medical image/video transmission
- Wireless surveillance





FSO technology – Channel modeling



- There are many factors affecting the optical power collected at the FSO RX, but there are ways to mitigate their effect

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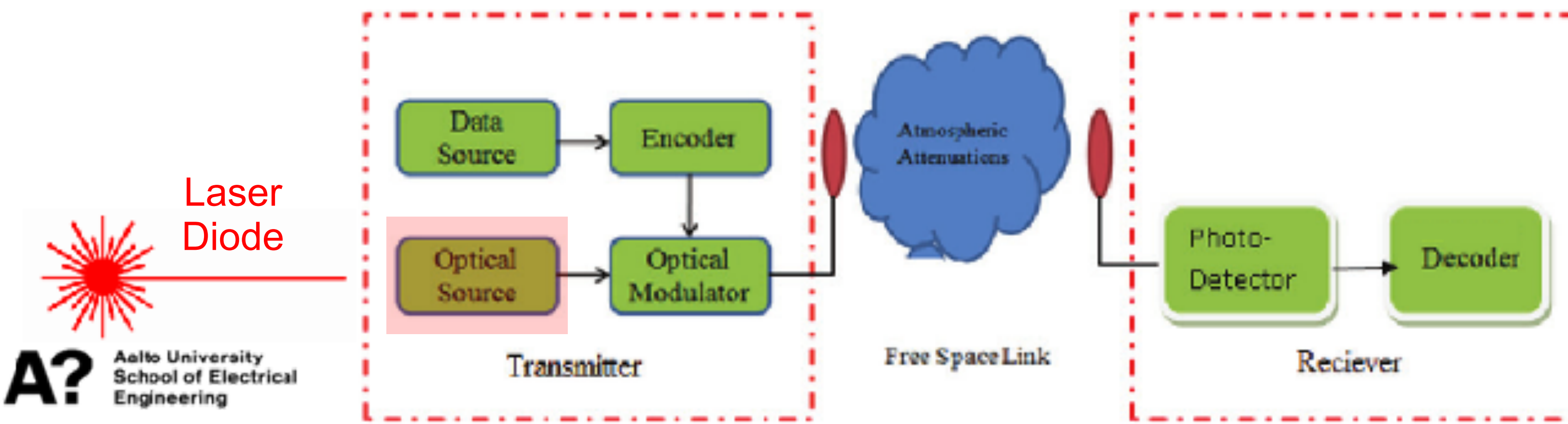
FSO technology – Transceiver architecture

- **Transmitter:** Modulates the optical carrier with the information waveforms produced by the source
- **Channel:** Transport the generated optical field through the atmosphere towards the destination
- **Receiver:** The EM field is optically collected, and a PD is used to convert the optical field into an electrical current



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Applications/use cases/verticals

… in which optical wireless communications technology may have an opportunity for massive adoption beyond 5G

OWC technologies – Opportunities

1. **Space and aerial.** Ground-to-space/air and inter-satellite links
2. **Underwater communications.** RF signals have strong absorption
3. **Optical "wireless" fiber.** Replacement of fibers with FSO links
4. **Wireless LANs (IEEE).** New interface of IEEE 802.11(bb)
5. **Mobile/Cellular Communications (3GPP) (5G, 5G+, 6G)**

- Role of OWC in the different procedures, technologies, and enablers of mobile networks (RIS signaling, carrier aggregation, dual connectivity)
- Verticals: Industry (automation); Vehicular commun. (V2V/V2I/V2X); MTC & massive/passive IoT; Joint Communications & Sensing (Positioning)

6. **Health care applications and medical use cases**

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Standardization Sector ITU-T

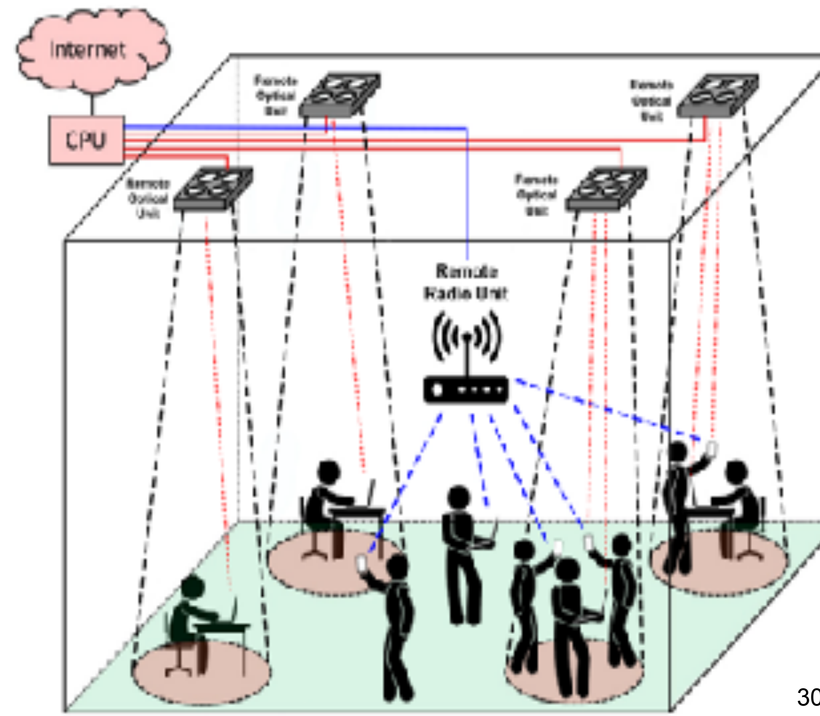
RF/Optical wireless access – System model

$$R_n = \sum_{i \in \mathcal{I}} \alpha_{i,n}\, r_{i,n}^{(\mathrm{RF})} + \sum_{j \in \mathcal{J}} \beta_{j,n}\, r_{j,n}^{(\mathrm{VLC})}$$

$\alpha_{i,n}, \beta_{j,n} \in [0, 1]$ are the scheduling weights.

Data rate per user receiving wireless communication resources in RF (α) and VLC (β) bands

RF/Optical wireless integration approach	Constraint on the number of RUs (radio and/or optical) per user
RF only	Each user is always served by one RRU
VLC only	Each user is always served by one ROU
RF-VLC Selection	Each user is always served by one RU (which is either RRU or ROU).
RF-VLC aggregation	No restriction.



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RF/Optical wireless access – System model

RF carrier networking sub-system

VLC carrier(s) networking subsystem

SINR (received signal)

$$\gamma_{i,n}^{(\mathrm{RF})} = \frac{|g_{i,n}|^2 P_i / L_{i,n}}{\underbrace{\sum_{k \in \mathcal{I}; k \neq i} |g_{k,n}|^2 P_k / L_{k,n}}_{\text{Inter-cell interference power}} + \underbrace{N_0 B_i}_{\text{AWGN power}}}$$

$$\gamma_{j,n}^{(\mathrm{VLC})} = \frac{\left(h_{j,n}\, \eta\, p_j\right)^2}{\underbrace{\sum_{k \in \mathcal{J}; k \neq j} \left(h_{k,n}\, \eta\, p_k\right)^2}_{\text{Inter-cell interference power}} + \underbrace{\sigma_n^2 W_j}_{\text{AWGN power}}}$$

Achievable data rate from one RU

$$r_{i,n}^{(\mathrm{RF})} = B_i \log_2\left(1 + \gamma_{i,n}^{(\mathrm{RF})}\right)$$

$$r_{j,n}^{(\mathrm{VLC})} = W_j \log_2\left(1 + \frac{e}{2\pi} \gamma_{j,n}^{(\mathrm{VLC})}\right)$$

Total data rate from RAT technology

$$R_n^{(\mathrm{RF})} = \sum_{i \in \mathcal{I}} \alpha_{i,n}\, r_{i,n}^{(\mathrm{RF})}$$

$$R_n^{(\mathrm{VLC})} = \sum_{j \in \mathcal{J}} \beta_{j,n}\, r_{j,n}^{(\mathrm{VLC})}$$

RF/Optical RAT – Four optimization problems

RF-only network (1)

$$\max_{\mathbf{A}} \sum_{n\in\mathcal{N}} \ln\left(\sum_{i\in\mathcal{I}} \alpha_{i,n} r_{i,n}^{(\mathrm{RF})}\right)$$

s.t. $C_1: \|\boldsymbol{\alpha}_{i*}\|_1 \leq 1, \forall i \in \mathcal{I}$

$C_2: \max\{\boldsymbol{\alpha}_{*n}\} = \|\boldsymbol{\alpha}_{*n}\|_1, \forall n \in \mathcal{N}$

$C_3: 0 \leq \alpha_{i,n} \leq 1, \forall i \in \mathcal{I}, \forall n \in \mathcal{N}$

VLC-only network(2)

$$\max_{\mathbf{B}} \sum_{n\in\mathcal{N}} \ln\left(\sum_{j\in\mathcal{J}} \beta_{j,n} r_{j,n}^{(\mathrm{VLC})}\right)$$

s.t. $C_1: \|\boldsymbol{\beta}_{j*}\|_1 \leq 1, \forall j \in \mathcal{J}$

$C_2: \max\{\boldsymbol{\beta}_{*n}\} = \|\boldsymbol{\beta}_{*n}\|_1, \forall n \in \mathcal{N}$

$C_3: 0 \leq \beta_{j,n} \leq 1, \forall j \in \mathcal{J}, \forall n \in \mathcal{N}$

Selection RF-VLC network (3)

$$\max_{\mathbf{A},\mathbf{B}} \sum_{n\in\mathcal{N}} \ln\left(\sum_{i\in\mathcal{I}} \alpha_{i,n} r_{i,n}^{(\mathrm{RF})} + \sum_{j\in\mathcal{J}} \beta_{j,n} r_{j,n}^{(\mathrm{VLC})}\right)$$

s.t. $C_1: \|\boldsymbol{\alpha}_{i*}\|_1 \leq 1, \forall i \in \mathcal{I}$

$C_2: \|\boldsymbol{\beta}_{j*}\|_1 \leq 1, \forall j \in \mathcal{J}$

$C_3: \max\{[\boldsymbol{\alpha}_{*n}^T, \boldsymbol{\beta}_{*n}^T]\} = \|[\boldsymbol{\alpha}_{*n}^T, \boldsymbol{\beta}_{*n}^T]\|_1, \forall n \in \mathcal{N}$

$C_4: 0 \leq \alpha_{i,n}, \beta_{j,n} \leq 1, \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \forall n \in \mathcal{N}$

Aggregated RF-VLC network (4)

$$\max_{\mathbf{A},\mathbf{B}} \sum_{n\in\mathcal{N}} \ln\left(\sum_{i\in\mathcal{I}} \alpha_{i,n} r_{i,n}^{(\mathrm{RF})} + \sum_{j\in\mathcal{J}} \beta_{j,n} r_{j,n}^{(\mathrm{VLC})}\right)$$

s.t. $C_1: \|\boldsymbol{\alpha}_{i*}\|_1 \leq 1, \forall i \in \mathcal{I}$

$C_2: \|\boldsymbol{\beta}_{j*}\|_1 \leq 1, \forall j \in \mathcal{J}$

$C_3: 0 \leq \alpha_{i,n}, \beta_{j,n} \leq 1, \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \forall n \in \mathcal{N}$

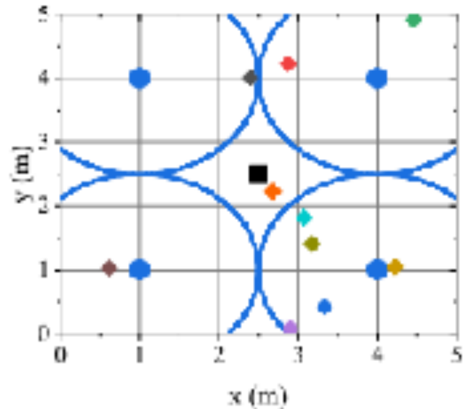
OMA is used in every RU. C_1 in (1), (2) and C_1, C_2 in (3), (4) ensures that RUs do not exceed the available resources

C_2 in (1), (2) and C_3 in (3) prevents a user from connecting to more that one RU

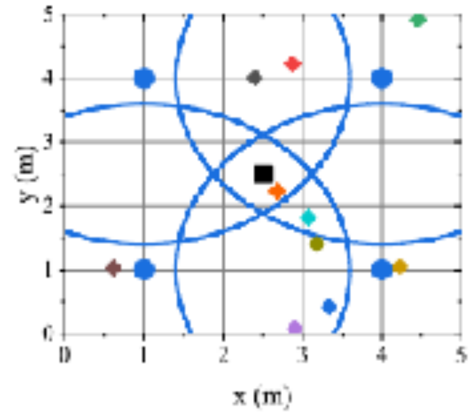
RF/Optical RAT – Simulation and results

No VLC overlapping

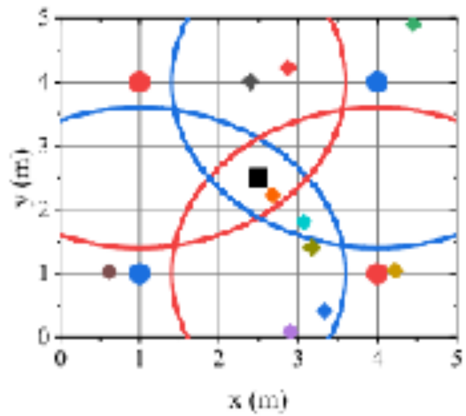
Four different layouts



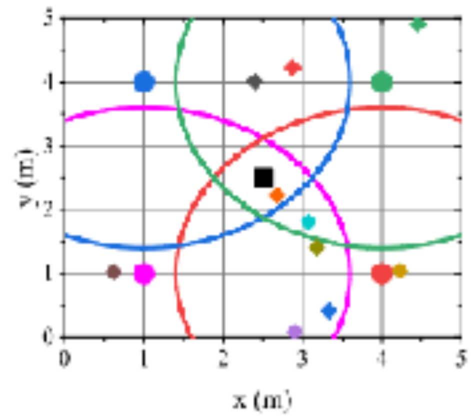
(a) $\Psi_{\max} = 45^\circ$, FR = 1.



(b) $\Psi_{\max} = 60^\circ$, FR = 1.

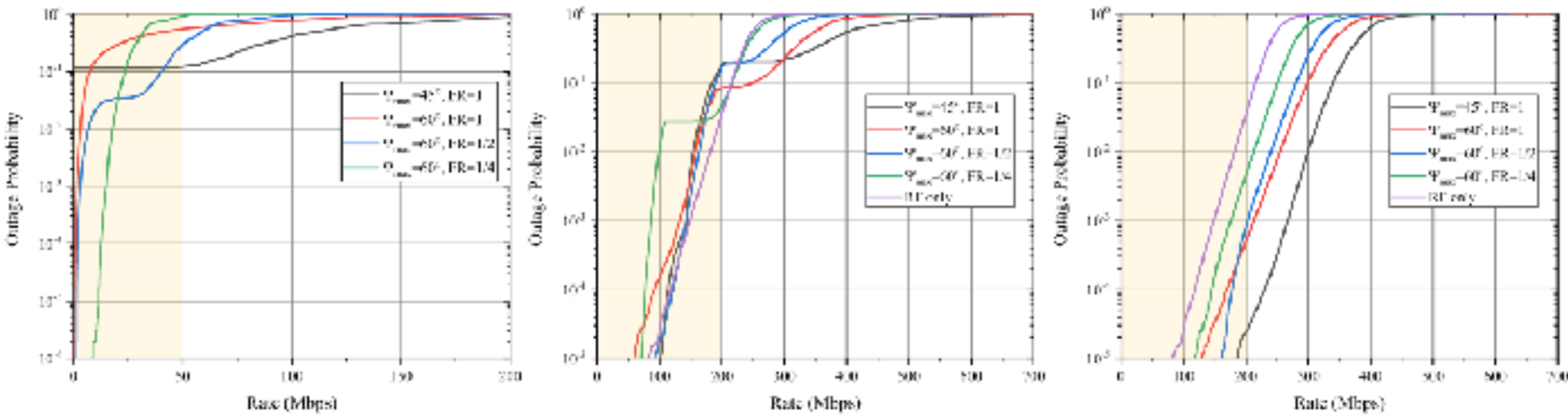


(c) $\Psi_{\max} = 60^\circ$, FR = 1/2.



(d) $\Psi_{\max} = 60^\circ$, FR = 1/4.

RF/Optical RAT – Performance figures

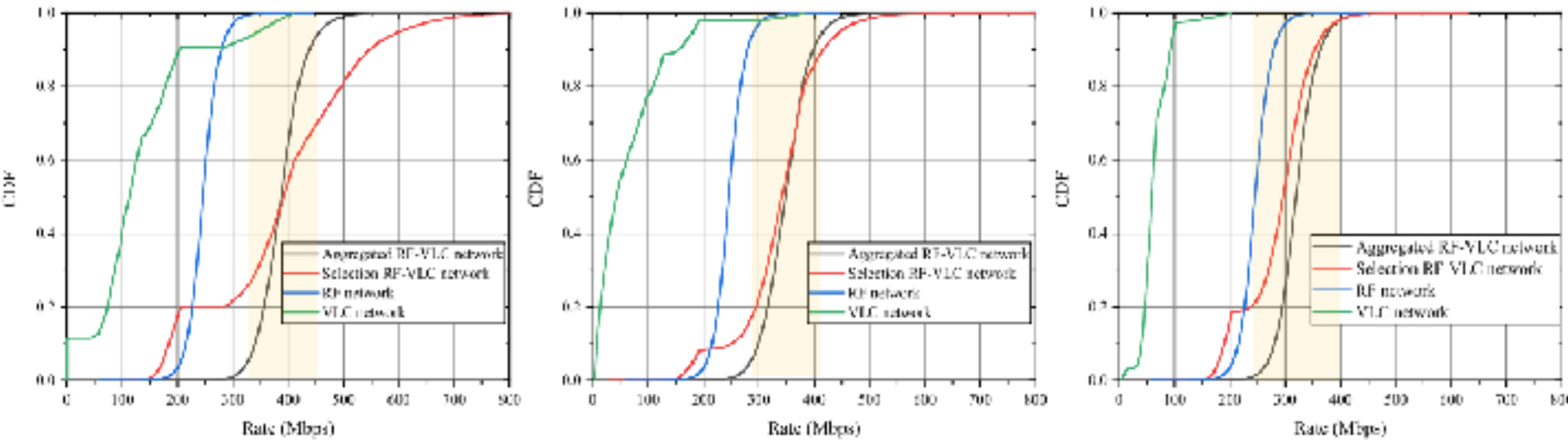


(a) VLC-only (b) RF-VLC Selection (c) RF-VLC aggregation

- In contrast to a VLC-only system, where full-coverage and low ICI are needed to enable URLLC, in RF-VLC networks it is not necessary to provide full-service coverage over VLC bands

In hybrid RF-VLC networks, full VLC coverage does not guarantee better results, due to inter-cell interference (ICI)

RF/Optical RAT – Performance figures



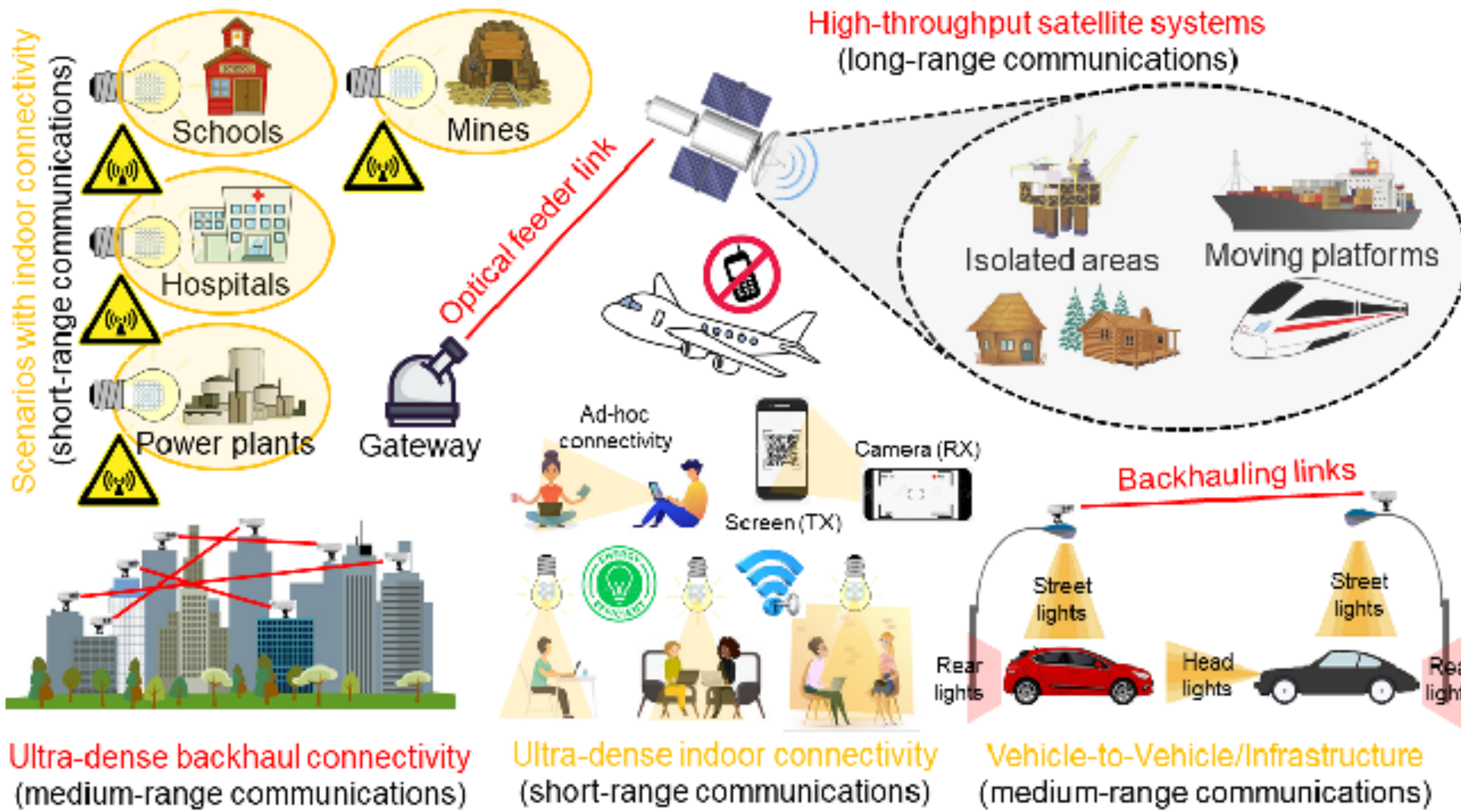
(a) No-overlapping VLC cells, FR factor = 1 (b) Overlapping VLC cells, FR factor = 1 (c) Overlapping VLC cells, FR factor = 1/2

- Hybrid RF-VLC networks have the potential to provide a solid solution to the new challenges that B5G indoor scenarios induce

Aggregation and selection of RF-VLC resources perform similar when it comes to the median of data rate (all figs)

Aggregation of RF-VLC resources outperforms every other curve when communication reliability is considered

OWC technologies – Closing ideas



Thanks for your kind attention!

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Further questions?
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