Light Fidelity (LiFi)

The technology, the opportunities and the challenges

Eduart Uzeir

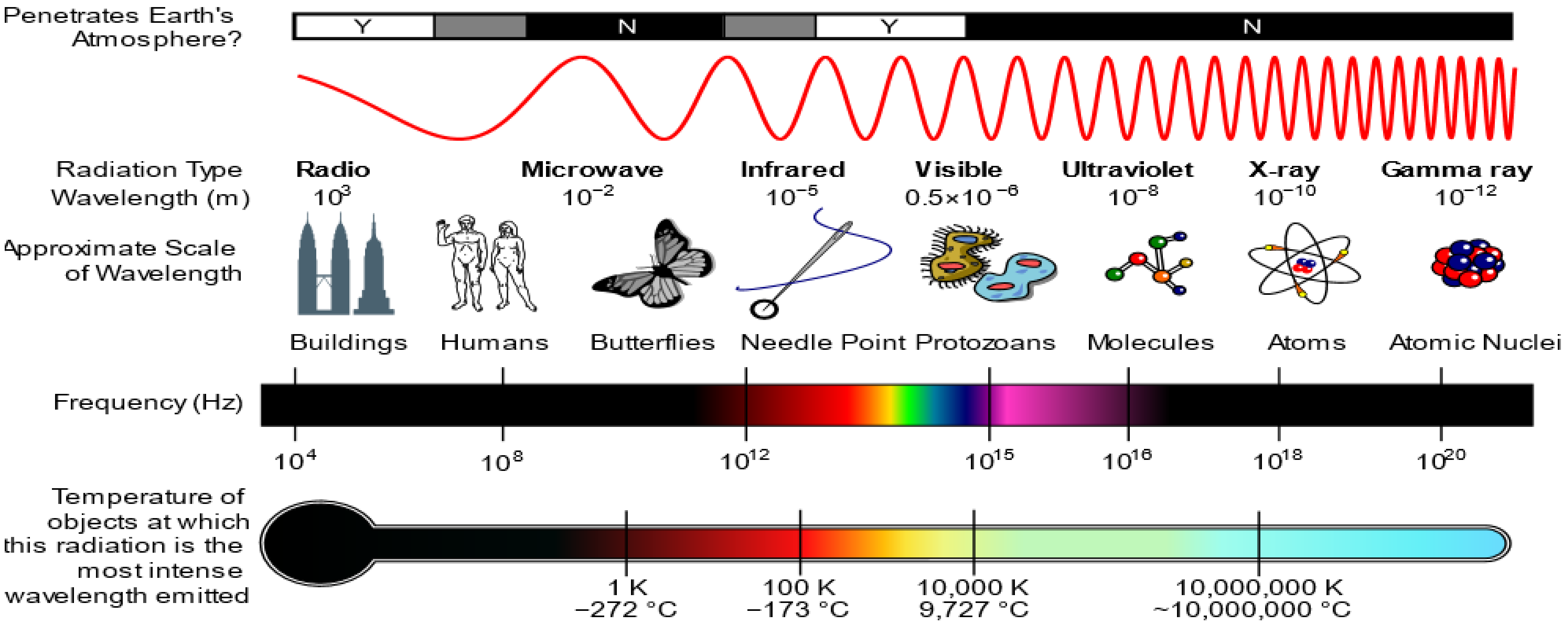
eduart.uzeir@studio.unibo.it

Master degree in Computer Science

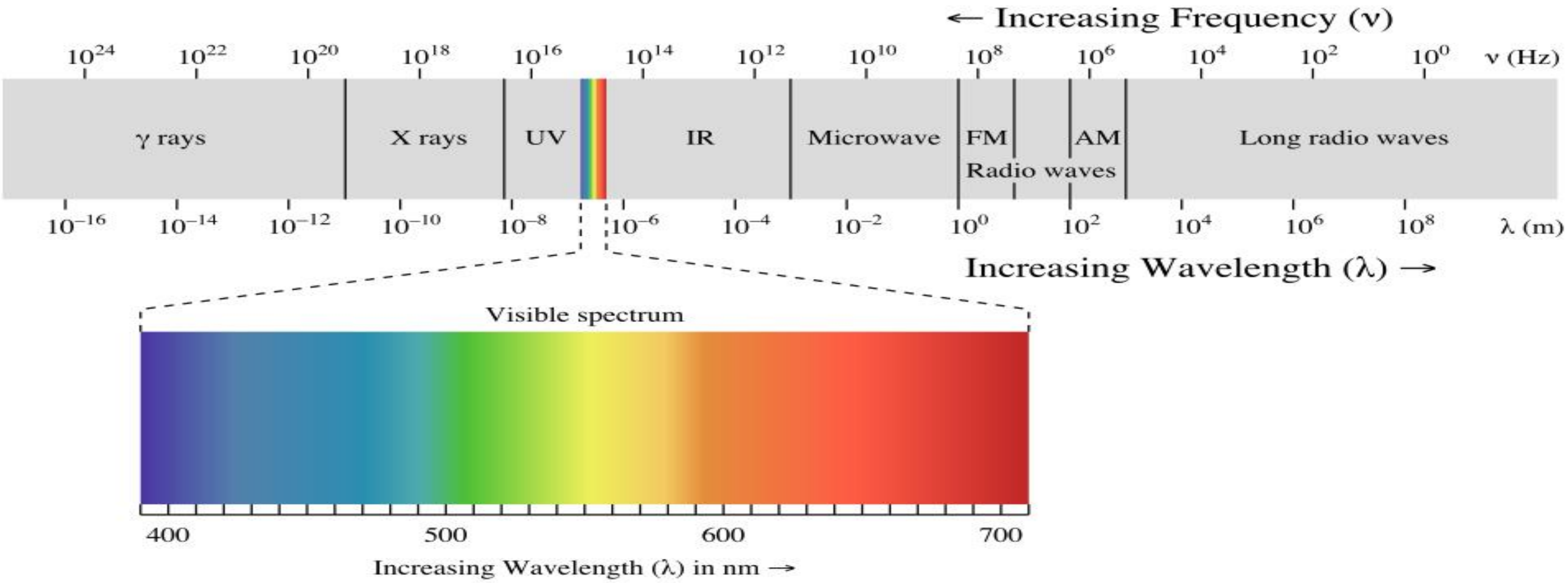
Agenda

- Electromagnetic Spectrum
- State of the art of wireless communications
- Optical Wireless Communication
- Visible Light Communication
- Light-Fidelity
- Conclusion

Electromagnetic Spectrum



Electromagnetic Spectrum

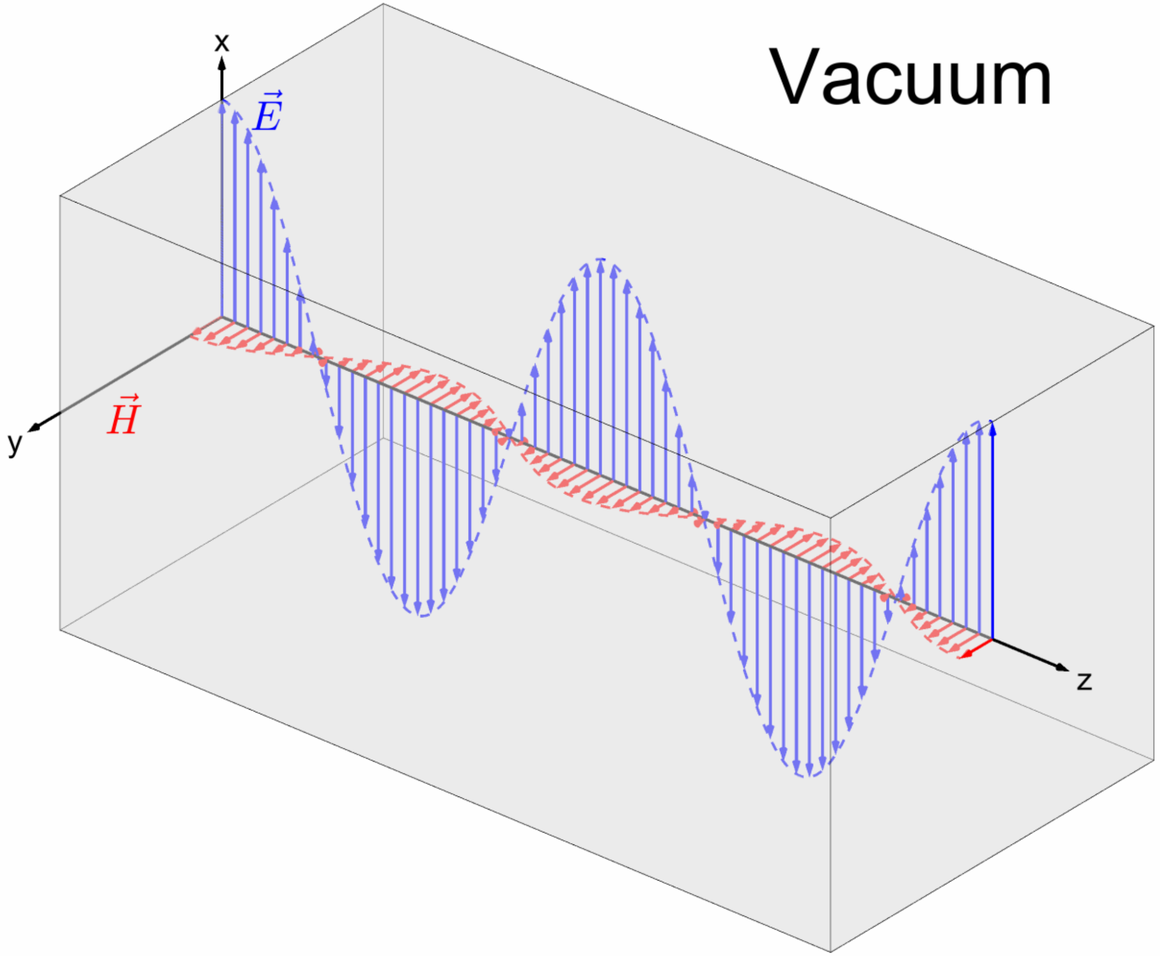


Electromagnetic Spectrum

Electromagnetic Waves

waves that are propagated through space by simultaneous periodic variations of electric and magnetic field intensity and that include radio waves, infrared, visible light, ultraviolet, X-rays, and gamma rays

Electromagnetic Spectrum



Electromagnetic Spectrum

➢ Wave characteristics

❖ Frequency :: number of times that the crest of a wave touch y-axes in the time unit (f = c/λ)

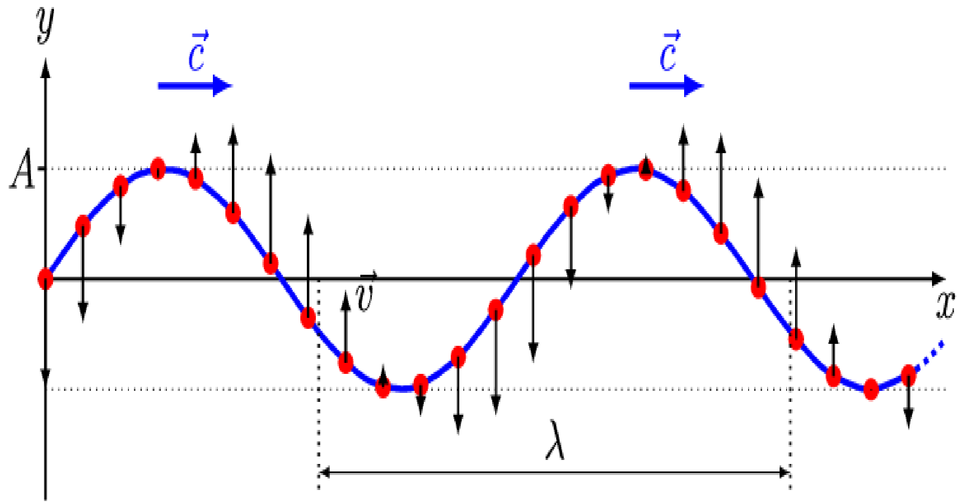
❖ Wavelength :: length between two continuous wave crests/troughs (λ = c/f)

❖ Amplitude :: quantity of energy contained in the wave

❖ Phase :: position in time of each point in the wave

➢ Sinusoidal function

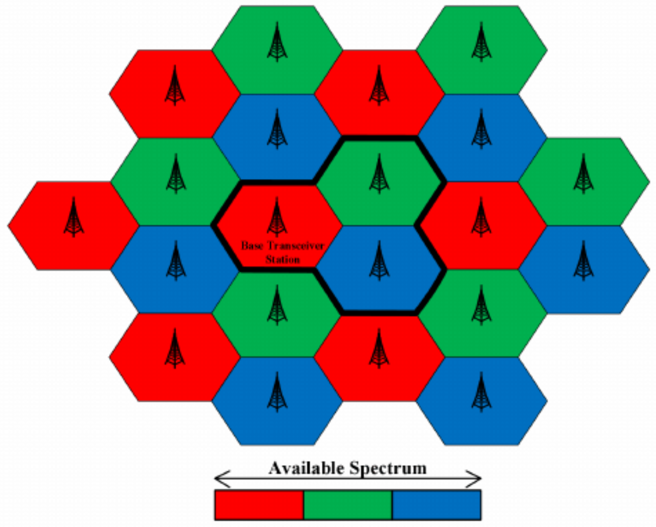
$$s(t) = A\sin(2\pi f t + \phi) = A\sin(\omega t + \phi)$$



State of the art

➢ Cellular Data Networks

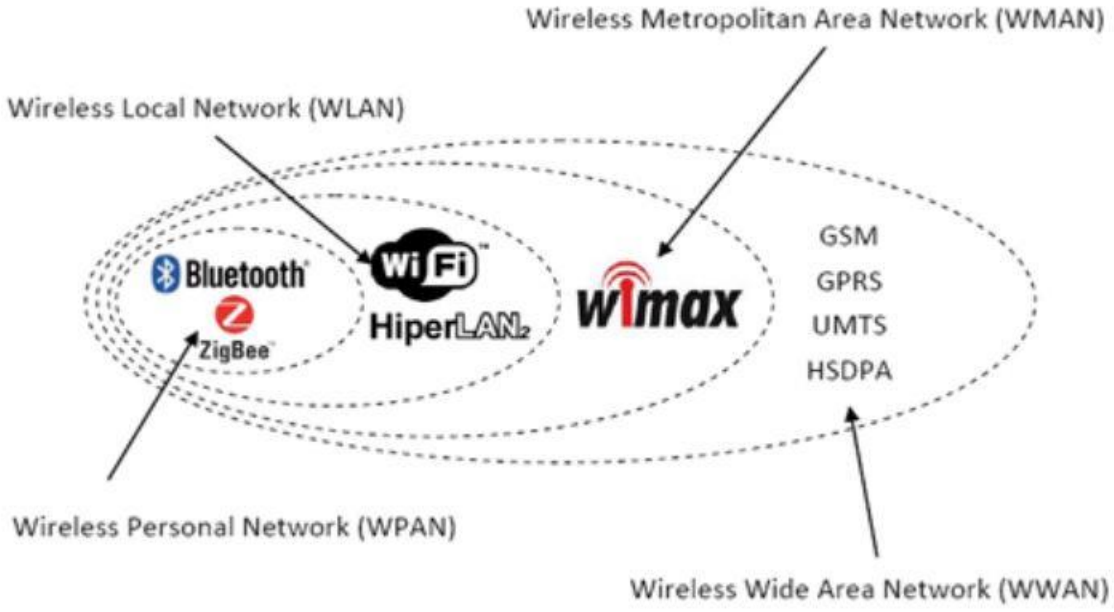
- ❖ bidirectional wireless communication systems based on space division and frequency reuse.
- ❖ reduce cell size to increase bandwidth and reduce energy consumption.
- ❖ small cells increase the complexity of the network.
- ❖ standards: IS-54, IS-95, IS-136, GSM, EDGE, LTE, 4G, 5G
- ❖ 5G (frequencies : [24 – 72 GHz]; speed : 2 Gbps)



State of the art

➢ Wireless Data Network

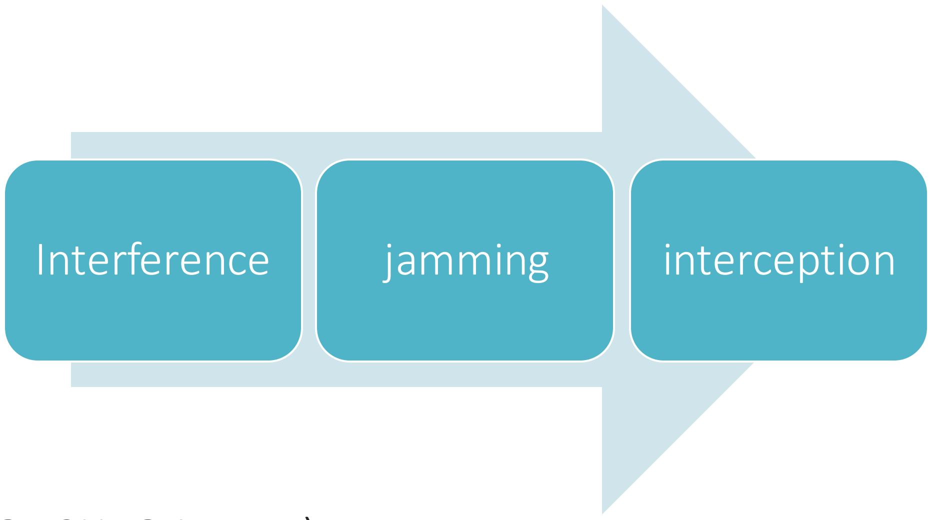
- ❖ IEEE family of international standards.
- ❖ classification by coverage range (WWAN, WMAN, WLAN, WPAN).
- ❖ WWAN (satellite, cellular)
- ❖ WMAN (town, cities) [802.16]
- ❖ WLAN (home, campus) [802.11]
- ❖ WPAN (rooms, body) [802.15]



State of the art

➢ WiFi (IEEE 802.11)

- operates in 2.4 GHz (λ = 120 mm) and 5 GHz (λ = 60 mm) frequency band.
- communication range between 20 and 150 m.
- maximum achieved speed ≈ 1Gbps.
- 2 implementations : Infrastructure and Ad Hoc networks.
- make use of SST (Spread Spectrum Technology) avoiding:



- supports QoS and power-management.
- IEEE 802.11 describes PHY and MAC layers.
- supports MIMO and various modulation schemes (OFDM, QPSK, QAM, ...).

State of the art

➢ WiFi (IEEE 802.11)

❖ most important standard releases

Standard	Year	Frequency Band	Speed	Modulation
802.11	1997	2.4 GHz	1-2 Mbps	DSSS-FHSS
802.11b	1999	2.4 GHz	11 Mbps	DSSS
802.11a	1999	5 GHz	54 Mbps	OFDM
802.11g	2003	2.4 GHz	54 Mbps	OFDM
802.11n	2009	2.4/5 GHz	65-600 Mbps	OFDM
802.11ac	2013	5 GHz	Up to 7 Gbps	MIMO-OFDM
802.11ax	2019	2.4/5/6 GHz	Up to 10 Gbps	MIMO-OFDM

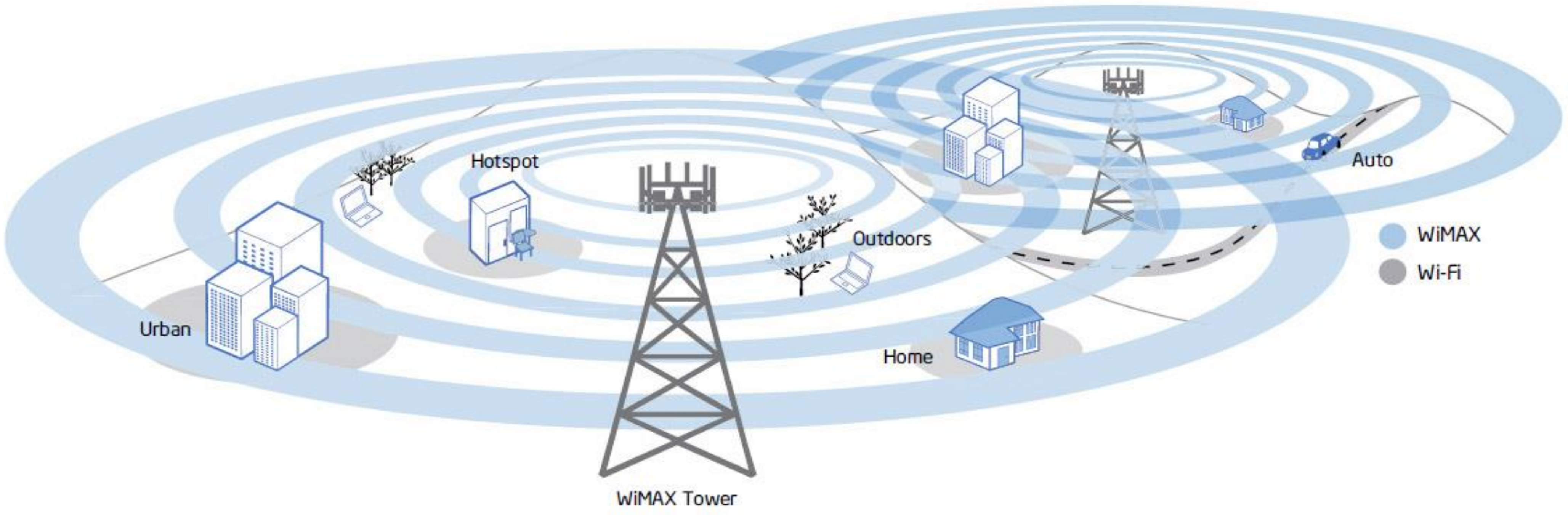
State of the art

➢ WiMAX (IEEE 802.16-2005)

- first deployment 2009.
- licensed frequency range 2.3 GHz, 2.5 GHz, 3.5 GHz but also unlicensed spectrum.
- transmission speed ≈ 1Gbps.
- “WiFi on steroids”, used for: broadband connections, backhaul, hotspots etc.
- support TDD and FDD.
- maximum operation range around 50 Km.
- IEEE 802.16 describes PHY and MAC layers.

State of the art

- WiMAX (IEEE 802.16-2005)



State of the art

➢ Bluetooth (IEEE 802.15.1)

❖ developed by Ericsson in the mid 90’ and reached the markets in 1999.

❖ frequency range 2.402 and 2480 GHz divided in 79, 1 MHz channels.

❖ packet-base protocol, implementing a master/slave protocol .

❖ together with ZigBee (IEEE 802.15.4) are classified as WPANs.

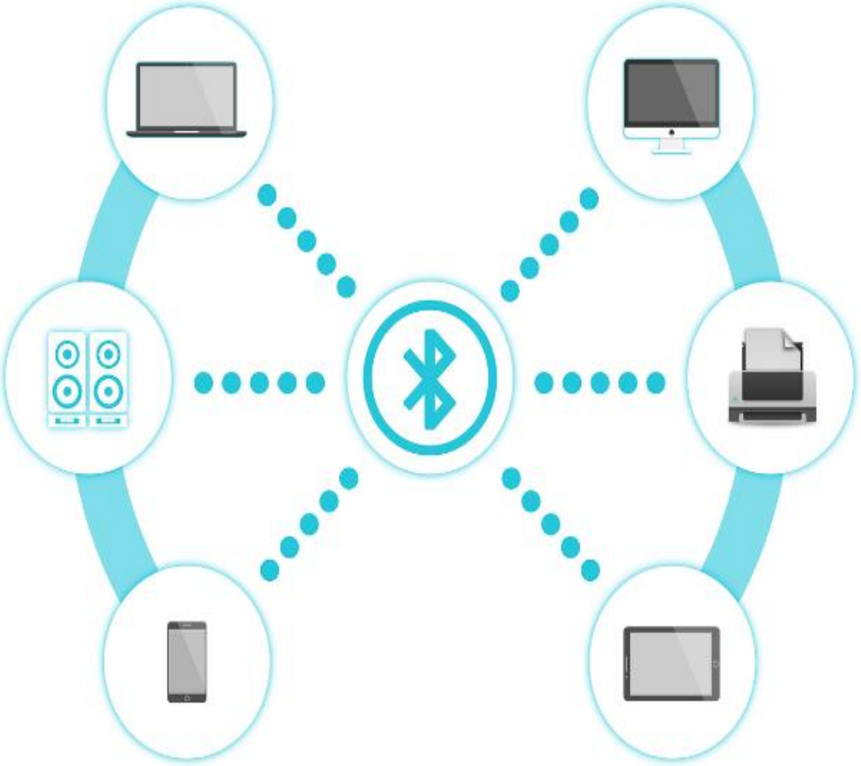
❖ development challenges: limited power devices, dynamic topology, ad hoc networks, interference avoidance, interoperability with millions of devices, low cost (~ 5$/chip).

❖ operation range around 10-15 m.

❖ extremely adoption in everyday use devices.

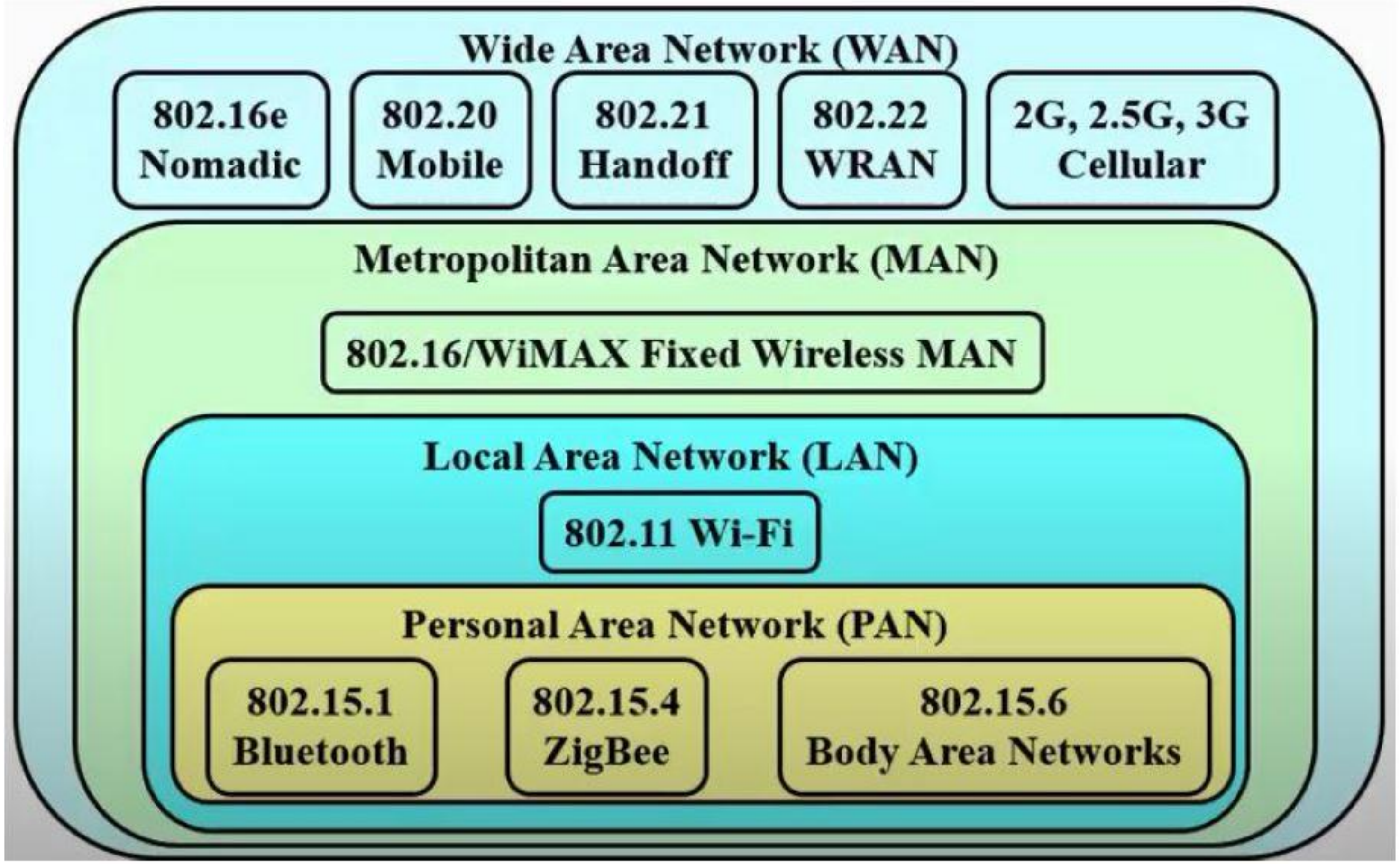
State of the art

- Bluetooth (IEEE 802.15.1)



State of the art

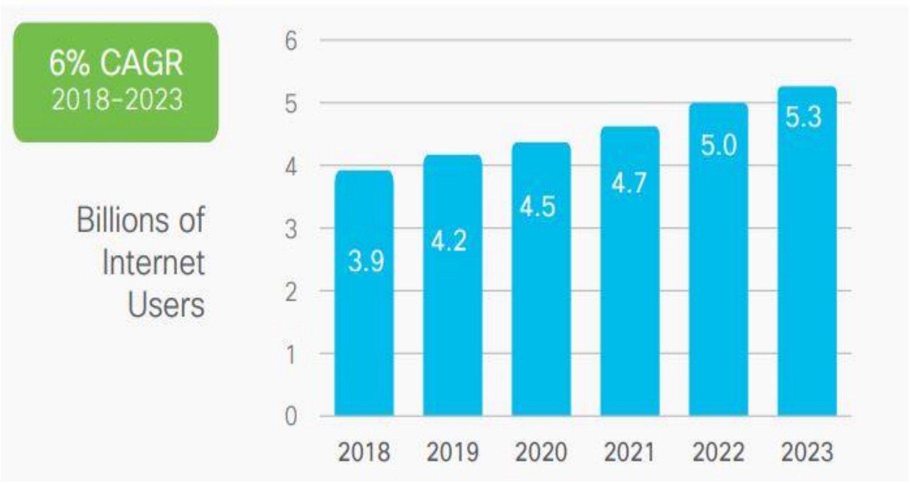
- Recap



Optical Wireless Communications

➢ CISCOs Annual Internet Report

- ❖ 15% + of World population access in Internet (2018-2023).
- ❖ number of Internet connected devices for person will increase from 2.4 to 3.6.
- ❖ data transmission speed must increase 3-fold, from 30 Mbps to 92 Mbps.



Region	2018	2019	2020	2021	2022	2023	CAGR (2018-2023)
Global	30.3	36.3	50.8	58.9	72.9	91.6	25%
Asia Pacific	34.5	42.2	62.3	80.2	98.5	116.1	27%
Latin America	10.6	12.1	25.1	27.3	30.4	34.6	27%
North America	46.9	56.8	70.7	87.3	98.4	109.5	18%
Western Europe	30.8	36.3	53.4	64.7	79.4	97.4	26%
Central and Eastern Europe	22.6	24.1	30.0	35.4	42.9	52.7	18%
Middle East and Africa	7.0	7.9	16.3	18.6	21.9	25.7	30%

Optical Wireless Communications

- Challenges and opportunities
  - limited and licensed radio spectrum is the bottleneck of modern requirements.
  - new standards and technologies need to be concieved.
  - different regions of EM must be explored [IR, VL, UV].
- OWC
  - the set of methods and technologies that relay on optical carriers to transmit data.

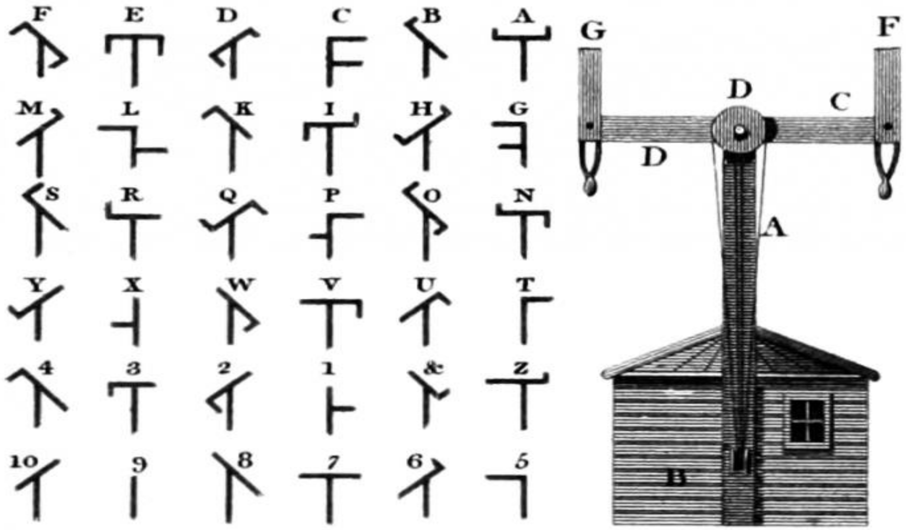
Spectrum Range	Frequency Range	Wavelength	Applications
Infrared	300 GHz – 30 THz	700 nm – 1 mm	nightvision, thermography, communication (IrDA)
Visible Light	430 THz – 790 THz	400 nm–700 nm	illumination, communication
Ultraviolet	790 THz – 30 PHz	10 nm – 400 nm	photography, sanitary, industry etc

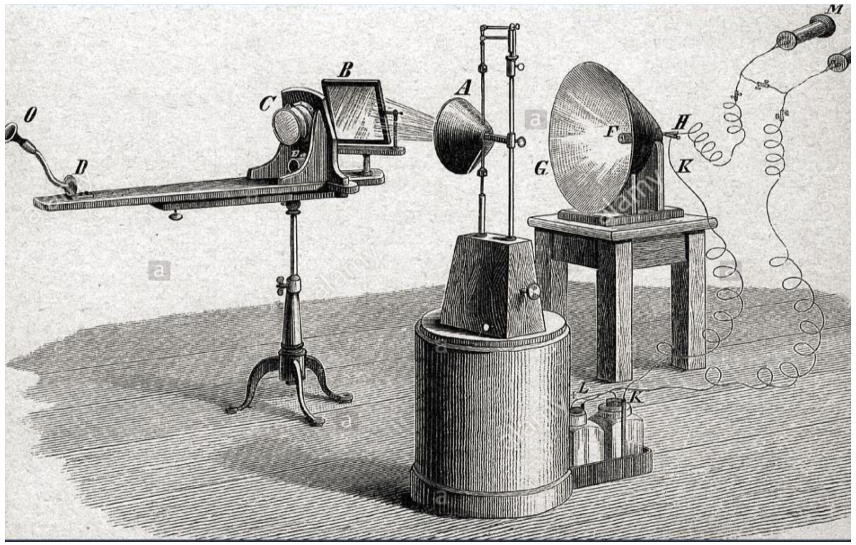
Optical Wireless Communications

➢ OWC timeline ...

- smoke signals
- optic telegraph of Claude Chappe [1790].
- photophone by Alexander Graham Bell [1880].
- discovery of Light Emitting Devices (LED) [1960].
- MIT experiment using GaAS LED to transmit a TV signal through 48 Km distance [1962].
- MIT experiment using He-Ne laser to transmit an acoustic singal through 190 Km [1963].
- first comercial application in Japan by NEC, an inter-citty link through 14 Km distance [1970].
- Inactivity ... (focus on RF).
- re-descovered potential in the XXI century.

Optical Wireless Communications





Optical Wireless Communications

OWC benefits

huge unallocated, free band [300 GHZ – 30 PHz]

solve security issues through physical characteristics of light

easy adoption with existing technologies [hybrid systems]

cost efficiency solutions based on "off the shelf" hardware

Optical Wireless Communications

- OWC classification based on the EM used band
  - Free Space Optics (FSO) [IR spectrum : λ = 750 – 1600 nm].
  - Visible Light Communications (VLC) [VL spectrum : λ = 390 – 750 nm].
  - Ultraviolet Communication (UVC) [UV spectrum : λ = 200 – 280 nm].
- OWC classification based on coverege range

Type	Range	Technology	Application Areas
Ultra-short range	millimeters	2.4 GHz	Inter-chip links
Short range	centimeters	2.4 GHz	WBAN, WPAN
Medium range	meters	5 GHz	WLAN, UWC
Long range	kilometers	2.4 GHz	WMAN, backhauls
Ultra-long range	> 10'000 Km	2.4/5 GHz	Satellites

Visible Light Communication

- ➢ VLC

- ❖ IEEE 802.15.7-2011, IEEE 802.15.7-2018
- ❖ VLC is a short-range, optical communication technology that operates in the visible range of EM spectrum, between 380 and 780 nm.
- ❖ data transmission by intensity modulation of light sources such as LEDs and LDs, faster than the human eye can perceive.
- ❖ very large free spectrum to be used for data communication [300 THz].
- ❖ progress strongly related with the progress of LEDs, LDs and Photodetectors.
- ❖ used to empower new technologies like IoT, Vehicular communication, M2M communication etc.

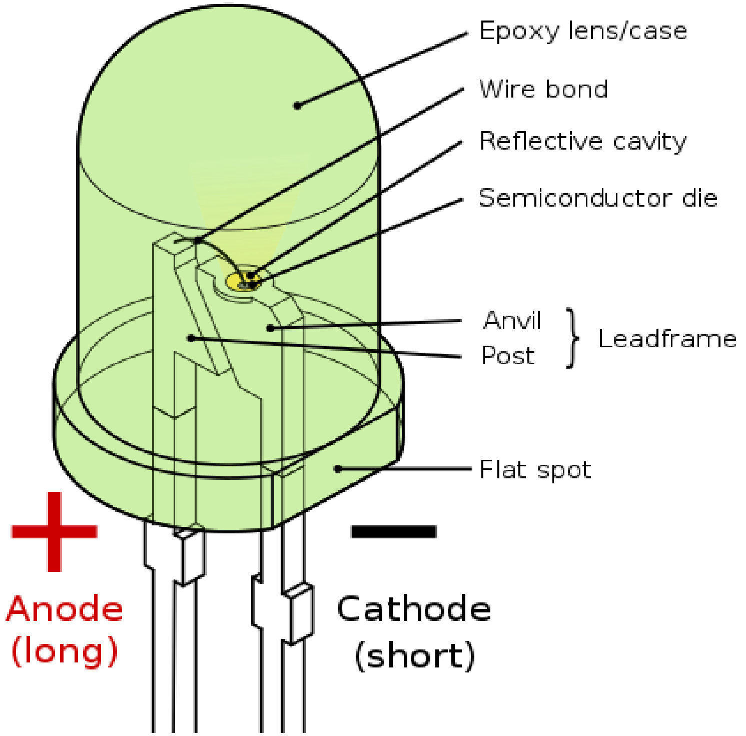
Visible Light Communication

➢ Light Emitting Diode (LED)

- ❖ electronically controlled solid state materials that can produce light when crossed by electric current.
- ❖ operation principle base on the physical effect of *electroluminescence*.
- ❖ explained by the atomic model of N. Borh and energetic levels.
- ❖ semiconductor materials: Ge, Si, C, Ga etc.

➢ Advantages of LEDs

- ❖ efficiency: high lm/W
- ❖ color: electronically controlled, no filters needed
- ❖ size: very small, chip integrated
- ❖ long lifetime: very high [35’000-50’000 h]
- ❖ dimming: electronically controlled



Visible Light Communication

➢ Laser Diode (LD)

❖ semiconductor devices similar to LEDs, able to convert electric energy directly into light.

❖ the physical characteristics [wavelength, phase, coherence] of the created beam depends on the semiconductor materials chosen.

❖ a myriad of application fields [fiber optic communications, barcode readers, printers, pointers, ...].

➢ Advantages of LDs

❖ fast response time: better than LEDs

❖ narrow but powerful beam

❖ very high capacity of focus even in a small diameter [1 μm]

Visible Light Communication

➢ Photodiodes

❖ semiconductor devices that convert light into electrical current [inverse operation mode of LED, LDs].

❖ electric current is generated when photons hit the photodiode surface and are absorbed by it.

❖ operation principle based on *photoelectric effect*.

❖ photodiode capabilities depends on the build materials.

❖ photodiodes play the role of the Receiver [Rx].

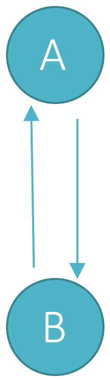
❖ drawback: response time inferior than LED, LDs.

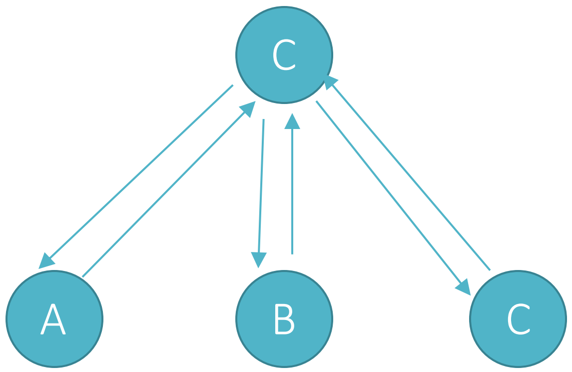
❖ usually used as photodetectors, cameras, remote control device.

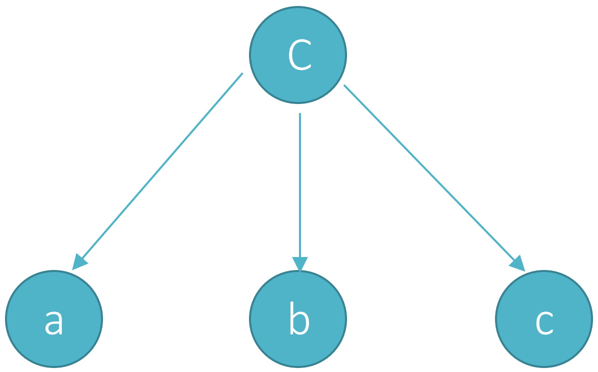
Visible Light Communication

➢ VLC Architecture

- ❖ IEEE 802.15.7-2018 standard defines 3 type of topologies for VLC networks [p2p, star, broadcast].
- ❖ each VLC device is identified by a unique 64-bit address in the network.
- ❖ VLC devices are divided in 3 categories [Infrastructure, Mobile, Vehicle].
- ❖ IEEE 802.15.7-2018 defines physical layer (PHY) and MAC sublayer of data-link layer.







Visible Light Communication

- PHY

❖ standard defines 6 types of PHY (I, II... VI).

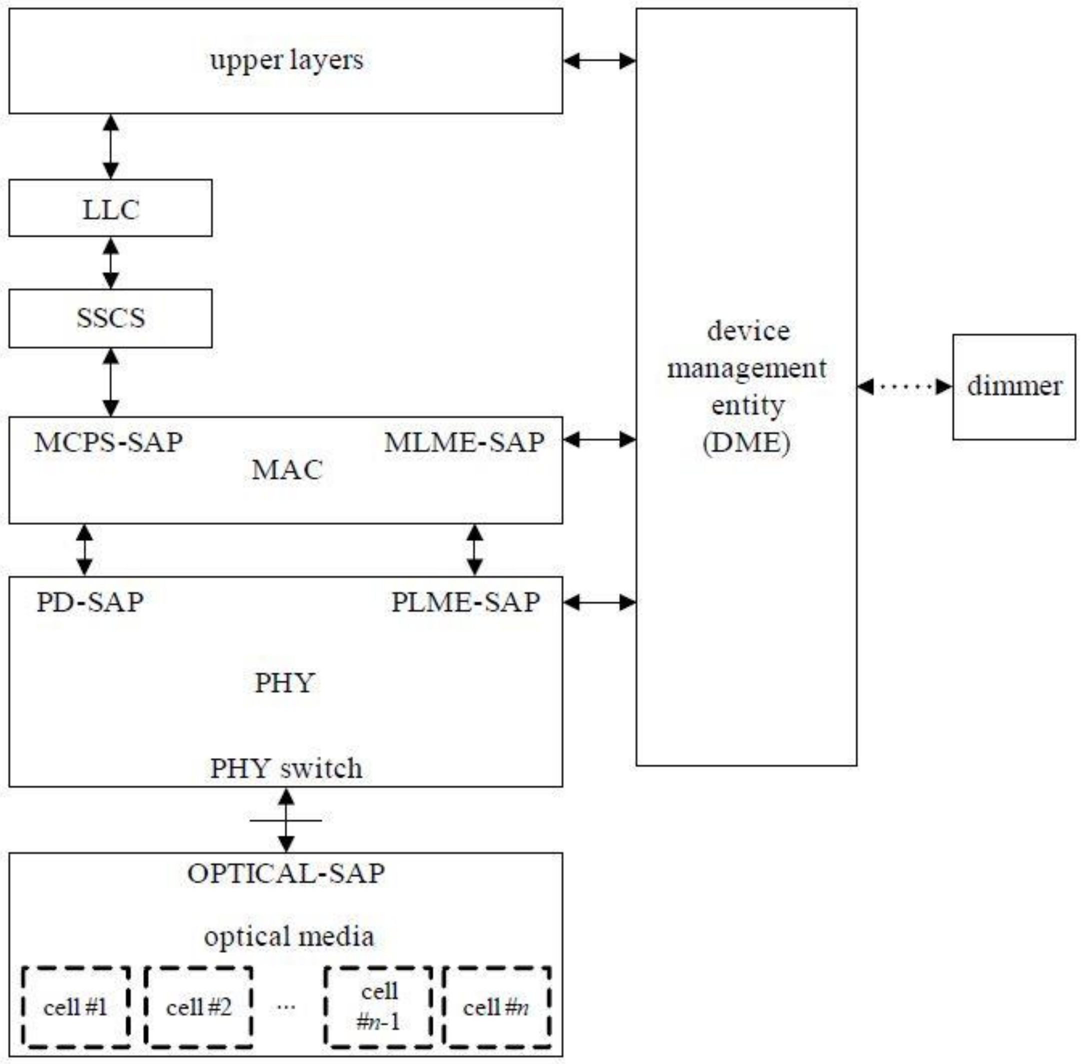
❖ contain 2 main components: PD-SAP, PLME-SAP.

❖ responsabilities:

1. Activation/deactivation of VLC transiver.
2. Channel selection.
3. Data transmission and reception.
4. Error correction
5. Synchronization.

❖ PPDU frame format.

Preamble (see 8.6.1)	PHY header (see 8.6.2)	HCS (see 8.6.3)	Optional fields (see 8.6.4)	PSDU (see 8.6.5)
SHR	PHR			PHY payload



Visible Light Communication

➢ MAC

❖ handle the access on PHY and creation of OWPAN.

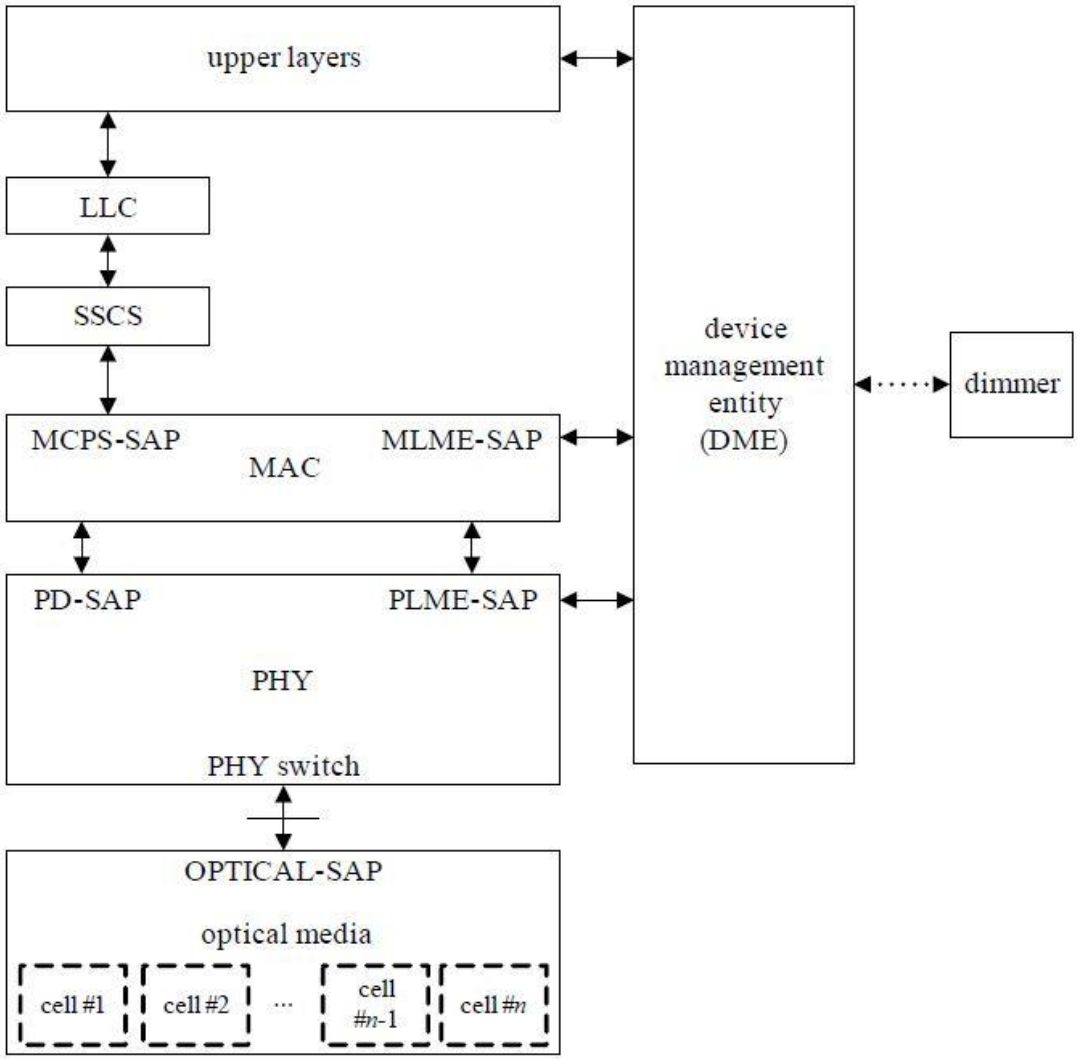
❖ responsabilities:

1. Generation/synchronization of network beacons.
2. Support for OWPAN association/disassocation.
3. Support visibility/dimming/flicker-mitigation.
4. Support device security, mobility and channel quality.

❖ MPDU frame format.

❖ 6 types of MPDUs [beacon, data, ACK, ...]

Frame Control (5.2.1.1)	Sequence Number (5.2.1.2)	Destination OWPAN Identifier (5.2.1.3)	Destination Address (5.2.1.4)	Source OWPAN Identifier (5.2.1.5)	Source Address (5.2.1.6)	Auxiliary Security Header (5.2.1.7)	Frame Payload (5.2.1.8)	FCS (5.2.1.9)
		Addressing fields						
MHR							MAC Payload	MFR



Visible Light Communication

➢ Modulation

- ❖ Is the process of imposing a data singal wave onto a carrier wave.
- ❖ PHY I, II, III used OOK, VPPM and CSK modulation, PHY IV, V, VI UFSOOK, S2-PSK etc.
- ❖ IEEE 802.15.7 support MIMO transmission and soffisticated modulations s.a: O-OFDM, DCO-OFDM.

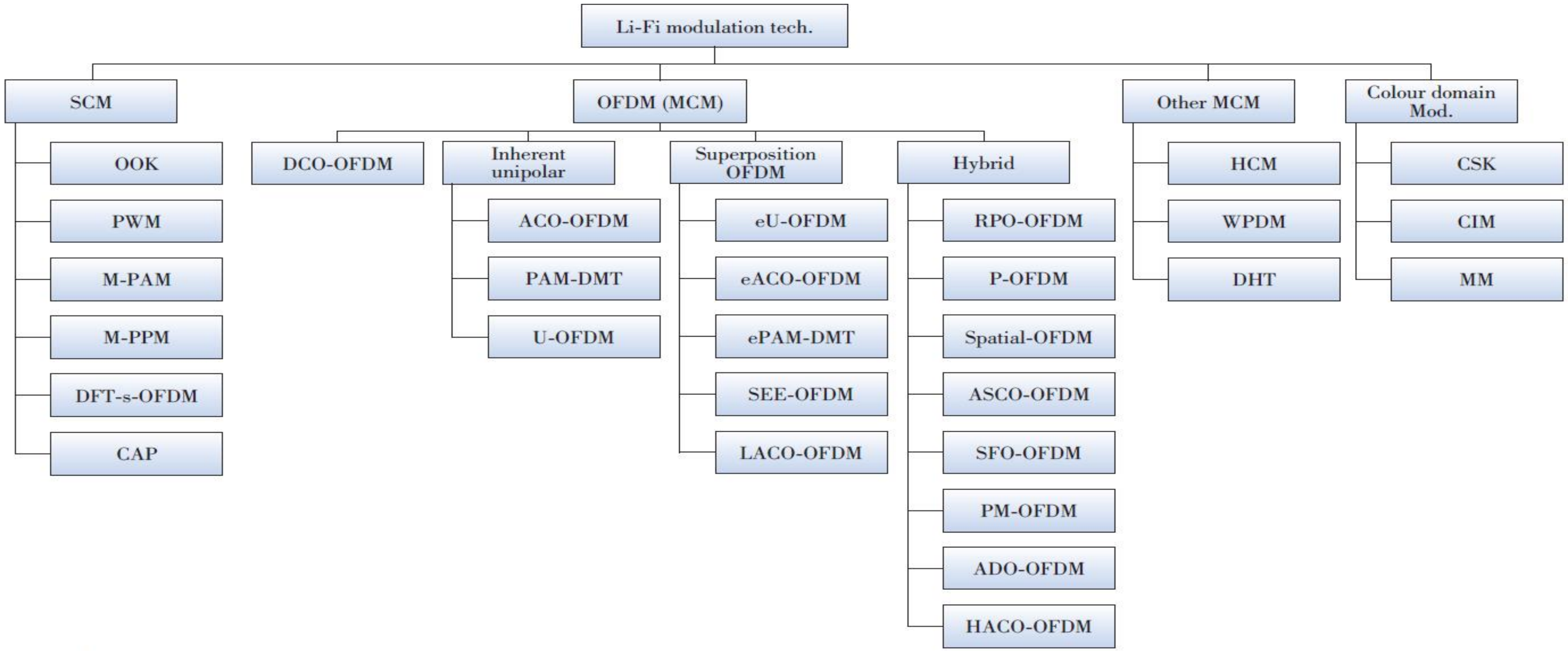
➢ Dimming

- ❖ controlling the perceived brightness of the light source based on user preference.
- ❖ dimming methods: add compensation symbols, cotrolling pulse width, controlling Amplitude.

➢ Flickering

- ❖ perceived brightness fluctuation [a disturbing effect coused by modulation].
- ❖ 2 types: Intraframe flicker, Interframe flicker.

Visible Light Communication



ACO-OFDM: asymmetrically clipped optical OFDM
ADO-OFDM: asymmetrically clipped DC biased optical OFDM
ASCO-OFDM: asymmetrically and symmetrically clipped optical OFDM
CAP: carrier-less amplitude modulation
CIM: colour intensity modulation
CSK: colour shift keying
DCO-OFDM: DC biased OFDM
DFT-s-OFDM: discrete Fourier transformation spread OFDM
DHT: discrete Hartley transform
eACO-OFDM: enhanced ACO-OFDM
ePAM-DMT: enhanced PAM-DMT
eU-OFDM: enhanced unipolar OFDM
HACO-OFDM: hybrid asymmetrically clipped optical OFDM
HCM: Hadamard coded modulation.
LACO-OFDM: layered ACO-OFDM
Li-Fi: light fidelity
MCM: multicarrier modulation
MM: metameric modulation
M-PAM: M-ary pulse amplitude modulation
M-PPM: M-ary pulse position modulation
OFDM: orthogonal frequency modulation
OOK: on-off keying
PAM-DMT: pulse amplitude modulation discrete multitone
PM-OFDM: position modulation OFDM
P-OFDM: polar OFDM
PWM: pulse width modulation
RPO-OFDM: reverse polarity optical OFDM
SCM: single carrier modulation
SEE-OFDM: spectrally and energy efficient OFDM
SFO-OFDM: spectrally factorized optical OFDM
WPDM: wavelet packet division multiplexing

Light Fidelity

➢ Evolution

❖ LiFi is the evolution of VLC into a full-fledged network infrastructure.

❖ term gain popularity in 2013, by a TedX speech of Harald Haas.

❖ from then many LiFi companies and research group [LiFi Consortium] with the promise to achieve more than 10 Gbps transmission speed.

❖ objective that have been achieved many time using various LED, LDs arrangements and modulation schmes. [Islim 2017, 10 Gbps], [Tsonev 2015, 100 Gbps]…

❖ estimated that global market for LiFi technology in 2024 will worth 101.3 Billion $.

❖ also LiFi is seen as a possible green wireless technology to empower 5G networks.

Light Fidelity

➢ Architecture of a LiFi network

❖ LiFi is a complete OWC system that enrich VLC with the possibility of bidirectional communication capability, by using different parts of the EM spectrum to achieve downlink and uplink connectivity.

❖ LiFi make use of a whole range of LED and LDs configurations to achieve parallel data transmission s.a array of parallel LEDs, RGB LEDs, etc.

❖ to construct a LiFi network we need to solve the follwing issues:

1. Multiple access: use of efficient modulation and ECC.
2. Bidirectional communication [uplink, downlink]: using different EM spectrum or hybrid solutions.
3. Full-duplex: by modulation FDD, TDD
4. Interference-free channels: assign different frequency range to each user and employ RGB LEDs.

❖ LiFi networks can be modelled as cellular-like network based on *attocells.*

Light Fidelity

➢ Architecture of a LiFi network

❖ atocells are smaller and with better spectral efficiency.

❖ each optical transmitter can act as an AP.

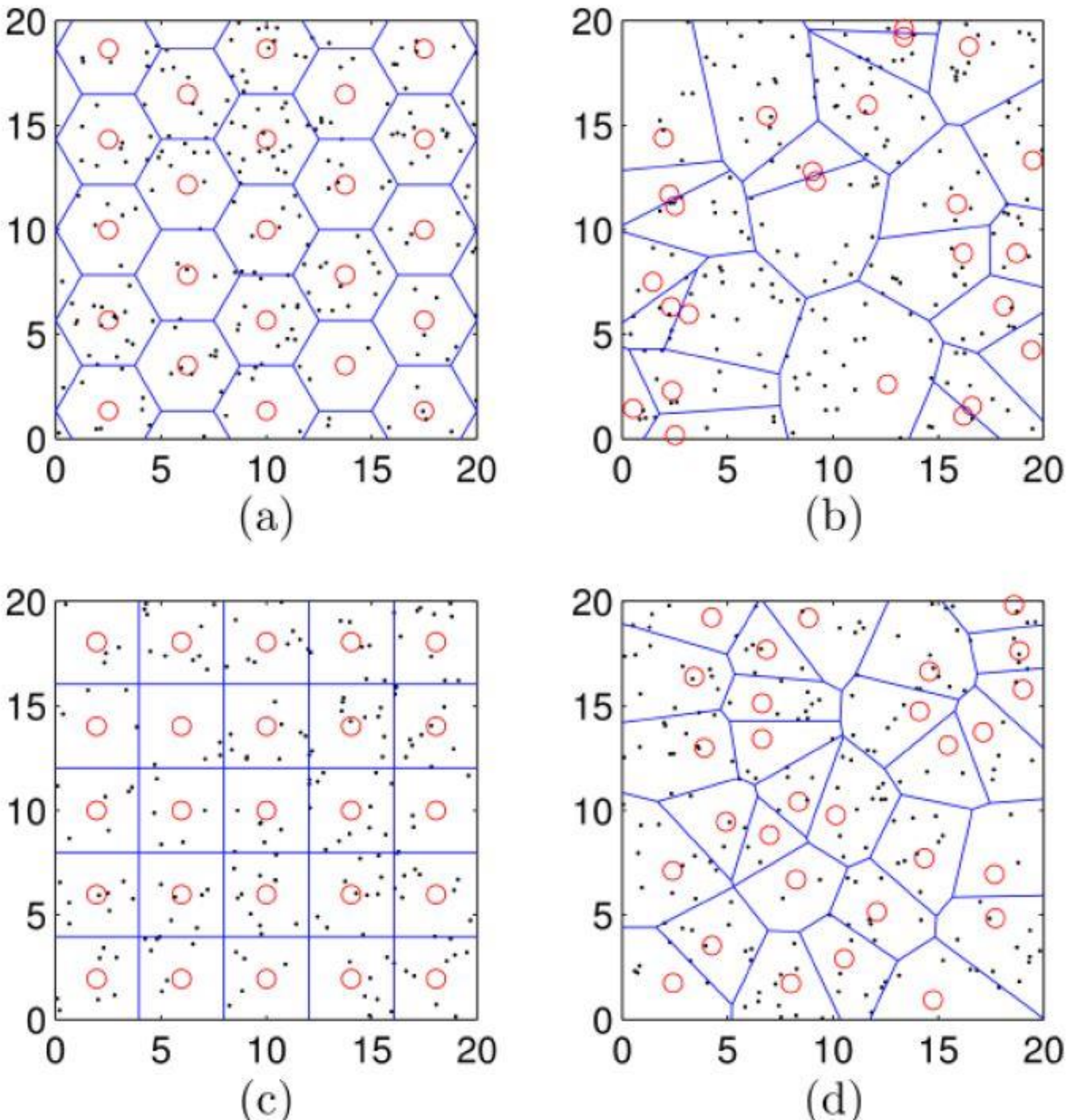
❖ models must implement strategies for:

1. User localization and allocation.
2. Load balancing.

❖ attocel networks can reach speeds in [12 – 48 Gbps].

❖ main components of each LiFi system are:

1. Optical source controller (driver).
2. One or many optical sources [LEDs, LDs].
3. Photodiode receiver.



(a) (b) (c) (d)

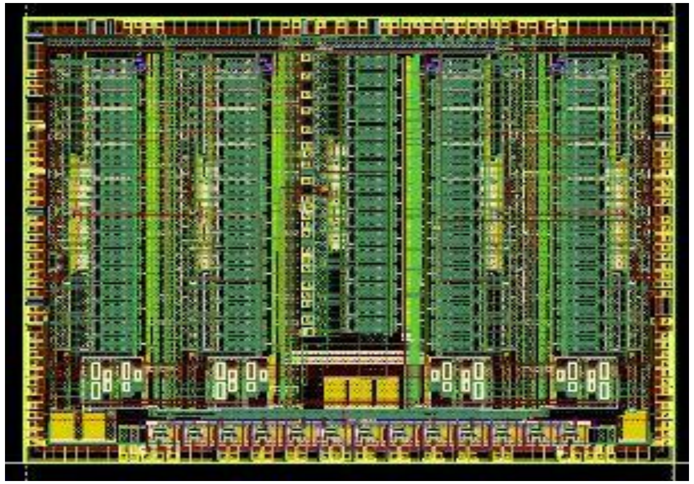
Light Fidelity

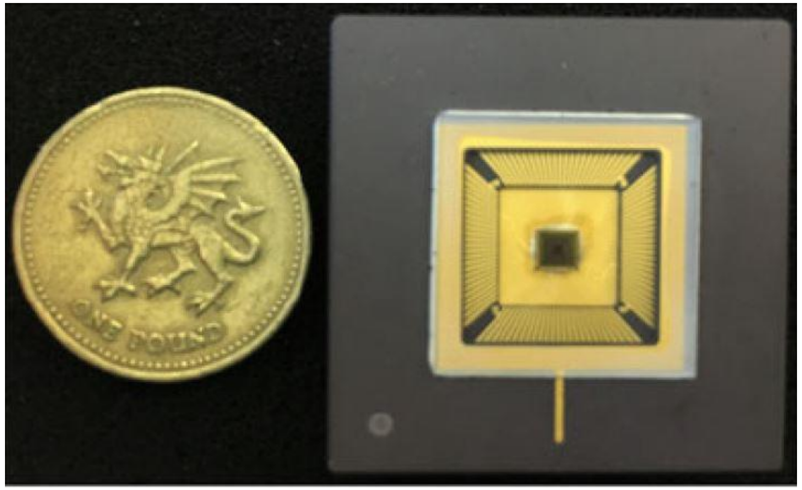
➢ Architecture of a LiFi network

❖ main components of each LiFi system are:

1. Optical source controller (driver).
2. One or many optical sources [LEDs, LDs].
3. Photodiode receiver.
4. Possible signal amplifiers.

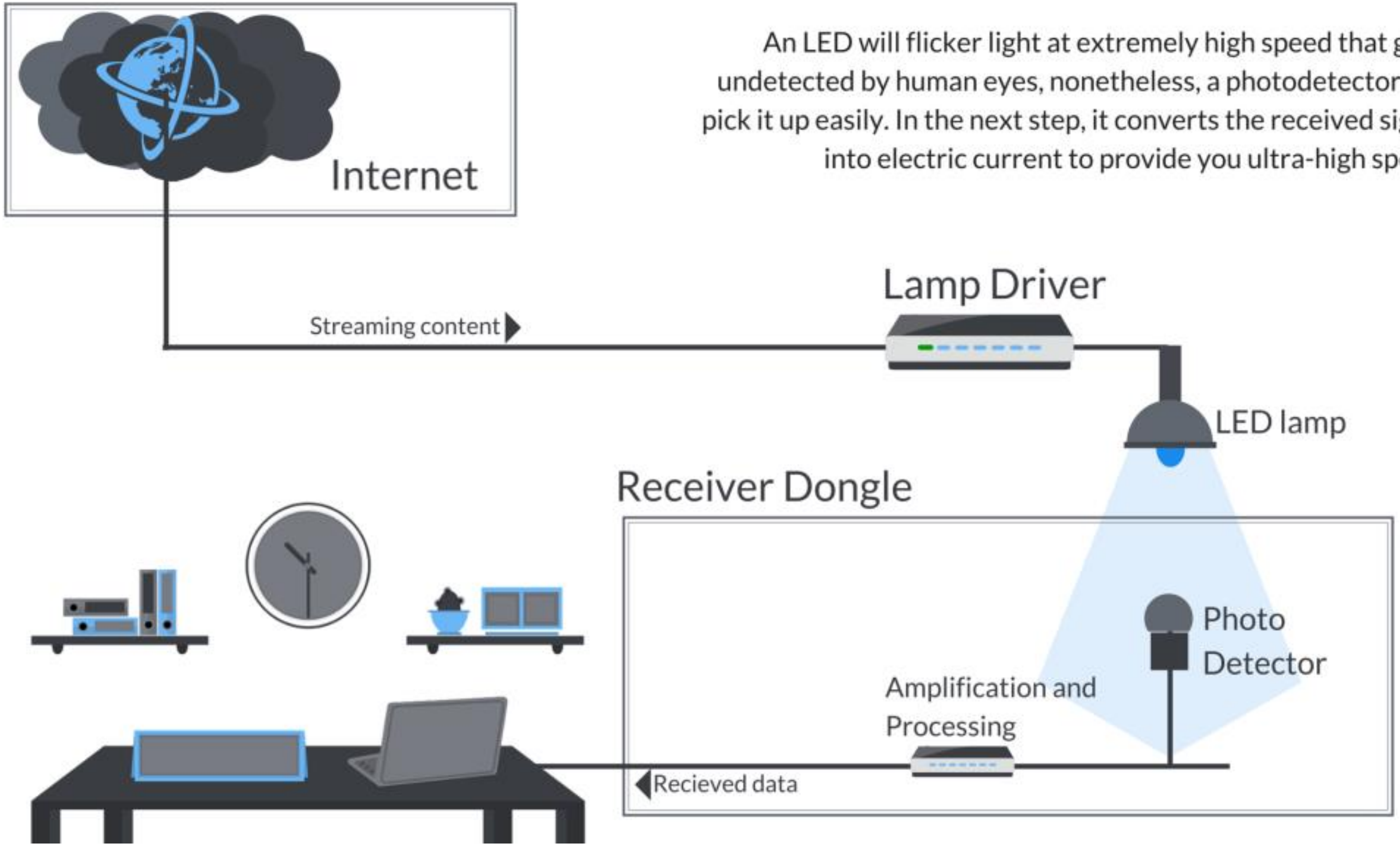
❖ ASIC components easy to manufacture [180 µm technology].





Light Fidelity

An LED will flicker light at extremely high speed that goes undetected by human eyes, nonetheless, a photodetector will pick it up easily. In the next step, it converts the received signal into electric current to provide you ultra-high speed.



Light Fidelity

➢ Advantages of LiFi

1. Use of light rather than RF as signal carrier allowing greater available spectrum range.
2. Can be used in RF prohibitive environments like hospitals, airplane cabins etc.
3. Underwater communication where WiFi is useless.
4. Widespread LEDs used for lighting can easily transform into LiFi APs.
5. Better sicurity due to physical characteristics of light.
6. LiFi can empower Vehicular and IoT communications.
7. LiFi provides higher transmission speed and data density.
8. LiFi devices are energy efficient.
9. LiFi is a safe green wireless communication technology.
10. LiFi is easy to combine with existing technologies s.a WiFi [hybrid systems].
11. Solar cells can be used as possible receiver in LoS data network achieving solar energy harvesting anc data communication. Experiments have shown 50 Mbps transmission speed [Lorriere 2020].
12. There is no need to develop new technologies, LiFi can be implemented with existing components.

Light Fidelity

➢ LiFi applications

❖ public illumination lamps using LEDs can be converted into AP providing internet access.

❖ automobile sector, vehicle communication and self-driving cars.

❖ industrial impiants and robotics avoiding RF interferences.

❖ underwater communications.

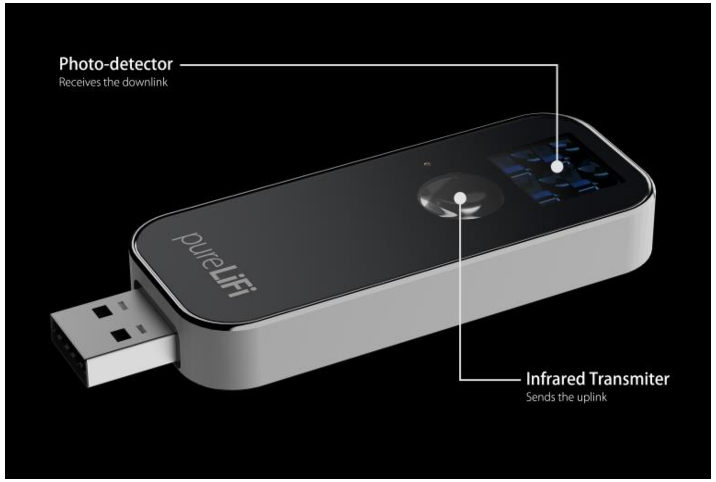
❖ IoT devices can use LiFi to communicate to each other and access Internet.

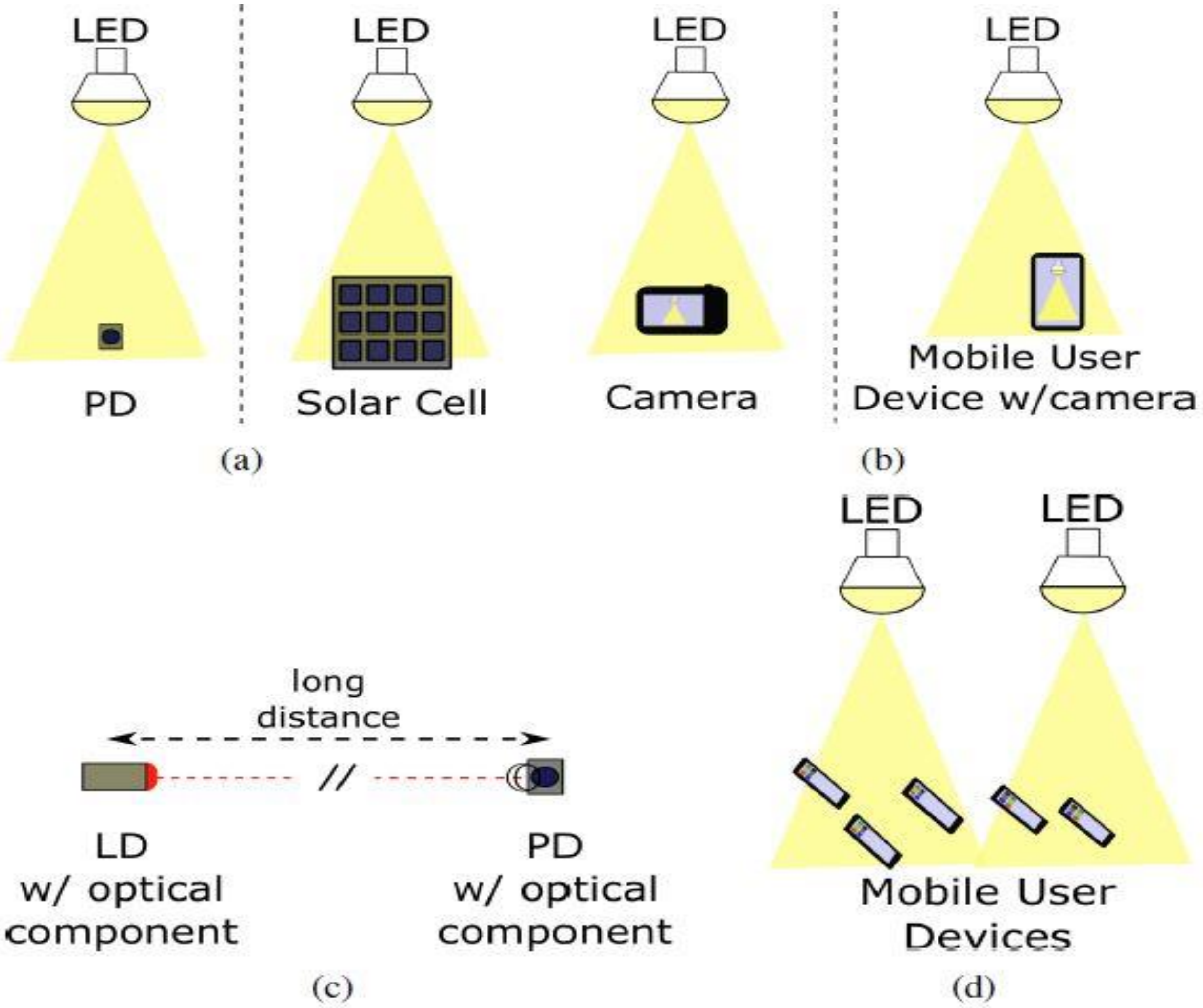
❖ virtual and augmented reality.

❖ ...

❖ many comercial solutions for in-door and out-door LiFi devices s.a [Firefly LiFi, Oleodocomm, PureLiFi, Signify, Velemenni, VLNcoom etc.

Light Fidelity





Light Fidelity

LiFi challenges

Improving receiver sensitivity.

Unlocking the full optical available bandwidth.

Conclusion

"I am turned into a sort of machine for observing facts and grinding out conclusions".

Ch. Darwin

Conclusions

- LiFi is a new and promising technology that can play a very important role in the future of wireless communications.
- It can be implemented using off the shelf hardware and combined with existing systems.
- LiFi offers high data transmission speed by exploiting a large range of EM spectrum.
- LiFi can be used where radio signals cannot.
- LiFi provide better communication security due to the physical characteristics of the carrier.
- LiFi can empower the next generation of wireless communications (5G and beyond).

References

- Bamiedakis.2016. "Wireless Visible Light Communications Employing Feed-Forward Pre-Equalization and PAM-4 Modulation."
- Bilnowski.2019. "Security of Visible Light Communication systems – A survey."
- Chen.2013. "Bidirectional 16-QAM OFDM in-building network over SMF and free-space VLC transport."
- Chi.2013. "Efficient and stable laser-driven white lighting."
- Chowdhury.2019. "Opportunities of Optical Spectrum for Future Wireless Communications."
- Demirkol.2019. "Powering the Internet of Things through Light Communication."
- Ferreira.2016. "High Bandwidth GaN-Base Micro-LEDs for Multi-Gb/s Visible Light Communications."
- George.2019. "LiFi for Vehicle to Vehicle Communication – A Review."
- Haas.2018. "LiFi is a pradigm-shifting 5G technology."
- Haas.2020. "Visible-light communications and light fidelity."
- Idris.2020. "Visible Light Communication: A potential 5G and beyond Communication Technology."

References

- Islam.2019. "Hybrid DCO-OFDM, ACO-OFDM and PAM-DMT for dimmable LiFi."
- Islim.2017. "Towards 10 Gb/s orthogonal grequency division multiplexing-base visible light communication using a GaN violet micro-LED."
- Khalid.2012. "1-Gb/s Transmission Over a Phosphorescent White LED by Using Rate-Adaptive Discrete Multitone Modulation."
- Liverman.2018. "WiFO: A hybrid communication network based on intefrated free-space optical and WiFi femtocells."
- Lorriere.2020. "Photovoltaic Solar Cell for Outdoor LiFi Communications."
- Minh.2008. "High-speed visible light communications using multiple-resonant equalization."
- Mukku.2019. "Integration of LiFi Technology in an Industry 4.0 Learning Factory."
- Tavakkolnia.2019. "MIMO System with Multi-directional Receiver in Optical Wireless Communications."
- Tsonev.2015. "Bidirectional 16-QAM OFDM in-building network over SMF and free-space VLC transport."

References

- Verma.2015. "Light-Fidelity (Li-FI): Transmission of Data through Light of Future Technology."
- Videv.2013. "Light-Fidelity (Li-Fi): Towards All-Optical Networking."
- Vucic.2010. "513Mbit/s Visible Light Communications Link Based on DMT-Modulation of a White LED."
- Watson.2013. "Visible light communications using a directly modulated 422 nm GaN laser diode."
- Wu.2013. "Performance Comparison of OFDM Signal and CAP Signal Over High Capacity RGB-LED-Based WDM Visible Light Communication."