IEEE 802 Standards on Light Communication

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Abstract

IEEE 802 recently finished new standards for optical wireless communications. 802.15.13 introduced a new MAC and two PHY layers enabling high reliability, low latency, and low power transmission for industrial wireless applications, and 802.11bb defines how to reuse the 802.11 MAC and OFDM-based PHYs over optical links, aiming at large-volume applications e.g., in enterprise and home scenarios. The tutorial presents major use cases, technical solutions, and recent technology demos in a variety of applications.

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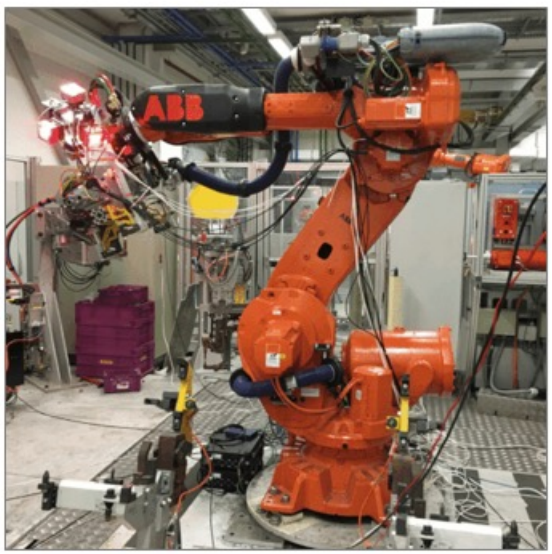
Outline

- What is Light Communication?
- IEEE P802.15.13
- IEEE P802.11bb
- Technology demos
- Summary

What is Light Communication?

Key facts

- **Mobile communication by using light**
- **Mobile, bidirectional, high-speed data**
- **Complementary to RF**



Unique selling points

- **Higher capacity/area in small "hotspots"**
  - 1…10 Mbps/m² (Wi-Fi 6…7), >100 Mbps/m² (LC)
- **High service quality: guaranteed delivery at low latency**
  - robust against jamming
  - deterministic channel access

Strategic use

- **RF is already mature and well established**
  - has issues in dense scenarios
- **LC adds new value to RF**
  - important synergies, both indoors and outdoors
- **Hybrid RF and LC is better than each technology alone**

- **What is LC?**
- Other LC standards

LC is useful where RF has limitations

Defence & Environment	Data & Industrial	Office & Commercial	Retail & Financial	Smart City & Transport	Consumer & Lifestyle

Field command	Data centres	Smart building	Indoor location	Smart city	Mobile devices
Secure comms	Industry 4.0	Secure comms	Shop analytics	Smart transport	Smart home
Harsh enviro	IoT sensors	Dense network	Payments	Streetlights	Entertainment
Underwater	Safe enviro	Net offload	Back office	Backhaul	Lighting

LC domains

- **Light allows connectivity over various distances**
- **Ultra short range**
  - inter-chip interconnects, in-body networks
- **Short-range**
  - optical WLAN, in-flight, car-to-X, indoor positioning, industrial wireless
- **Medium-/long range**
  - inter-building, mobile backhaul, underwater
- **Ultra-long range**
  - satellite feeder links, satellite-to-satellite

- **What is LC?**
- Other LC standards

Taxonomy of LC

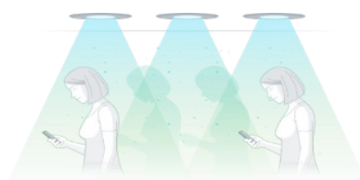
Differences types of light communications have different applications.

Optical Camera Communications

OCC

Low Speed
Geo Location
Advertisements
Notifications

Light Fidelity



LiFi

Secure high-speed
mobile wireless
communications

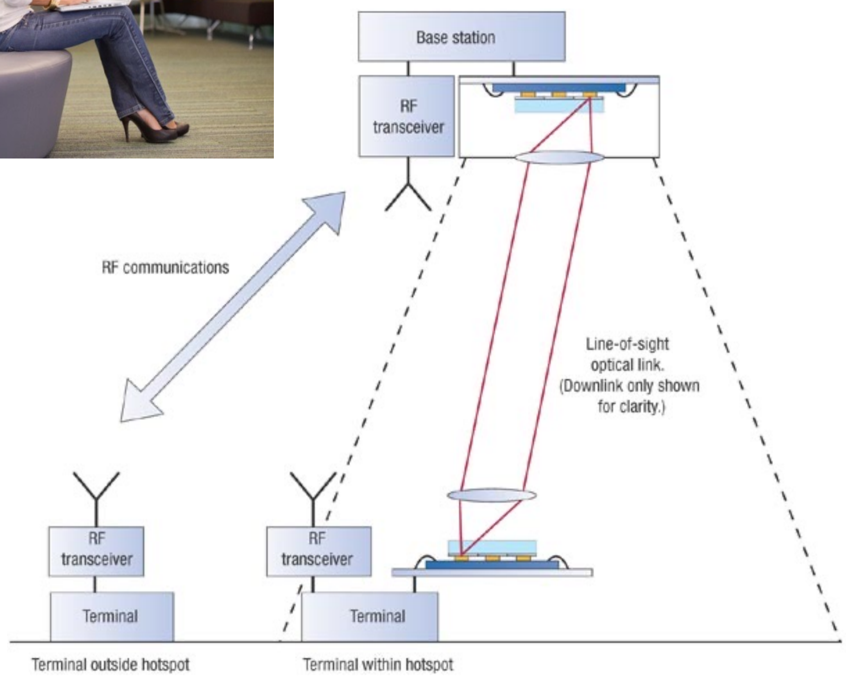
Free Space Optics

FSO

Backhaul
Long-distance
communications

- **What is LC?**
- Other LC standards

Hybrid RF/LC

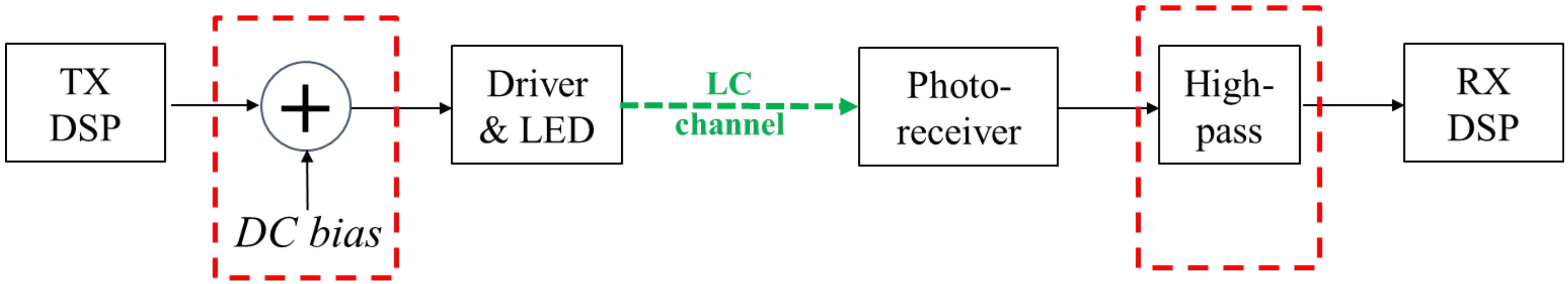


- **Optical small cells**
  - densify radio-based WLAN
  - using infrared or visible light
  - 100 Mbit/s … 10 Gbit/s per link
  - eventually integrated with lighting
- **Low-cost off-the-shelf components**
  - LEDs, laser diodes
  - silicon photodiodes
  - digital signal processing

Dominic O'Brien, Gareth Parry & Paul Stavrinou **Optical hot spots speed up wireless communications** Nature Photonics 1, 245 - 247 (2007)

- **What is LC?**
- Other LC standards

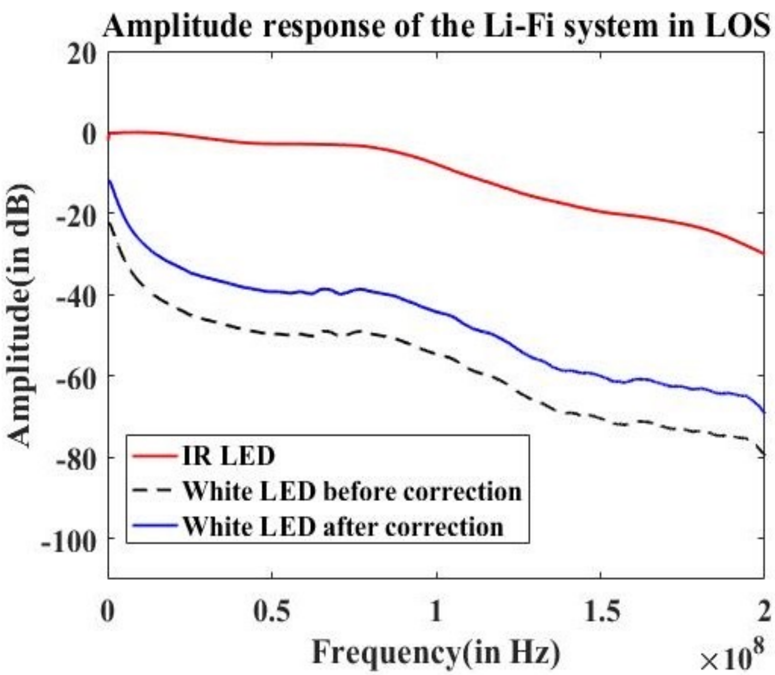
Basic LC link



- **TX and RX DSP can be very similar to RF.**
- **A real-valued waveform is needed and a bias is added.**
- **The biased waveform is transmitted by LED and detected by photodiode**
- **The high-pass removes the DC bias and possible ambient/sun light.**
- **Only the AC signal is used for communication, in the presence of thermal and shot noise.**

- Introduction
- **What is LC?**
- Other LC standards

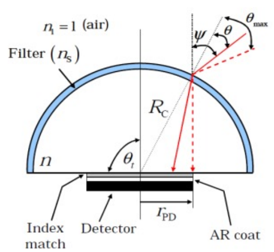
TX frontend

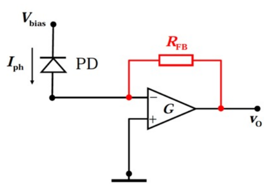


- **Any solid state light source can be used**
  - LEDs, Lasers and VCSELs support different bandwidth
- **802.15.13: UV, VIS and IR betw. 190 nm and 10000 nm**
  - intended for specialty applications
- **802.11bb supports IR between 800 an and 1000 nm**
  - compare IR versus visible light at same drive currents
- **IR has 10x more signal and 40x higher bandwidth**
  - conversion from blue to white, phosphor reduces the speed
  - higher e/o and o/e conversion coefficients in IR vs. blue

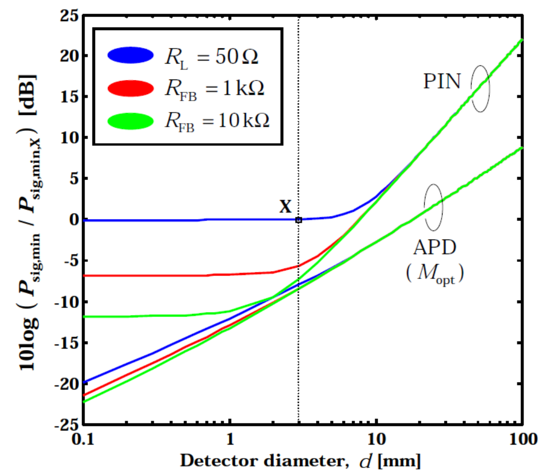
Sreelal M. Mana et al, "Experiments in Non-Line-of-Sight Li-Fi Channels," *2019 Global LIFI Congress*, Paris, France, 2019

RX frontend





- **PIN photodiode**
  - large area, limited sensitivity, low cost
- **Avalanche photodiode (APD)**
  - smaller area, higher sensitivity, higher cost
- **Optical concentrator (OC)**
  - increased effective area, reduced field-of-view
- **Transimpedance amplifier (TIA)**
  - small photocurrent (µA) into useful voltage (V)
- **Bootstrapping (BS)**
  - increases bandwidth

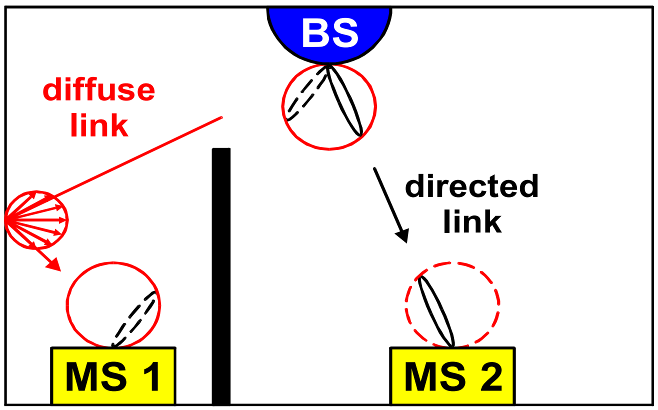


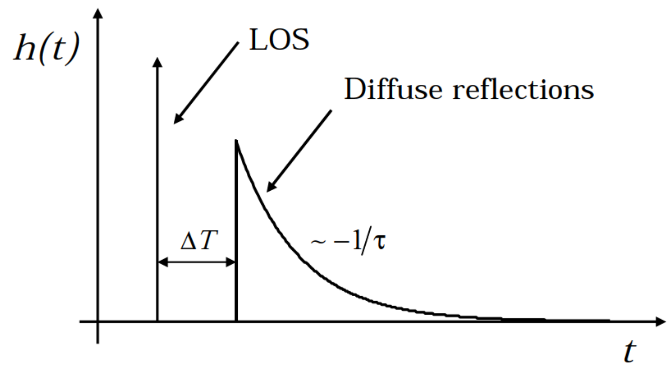
Jelena. Vucic, Ph.D. thesis, TU Berlin, 2009

- Introduction
- **What is LC?**
- Other LC standards

Light propagation

BS: base station, MS: mobile station

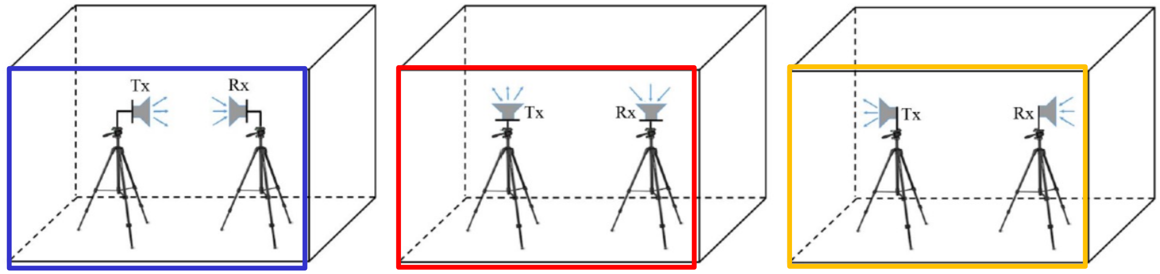


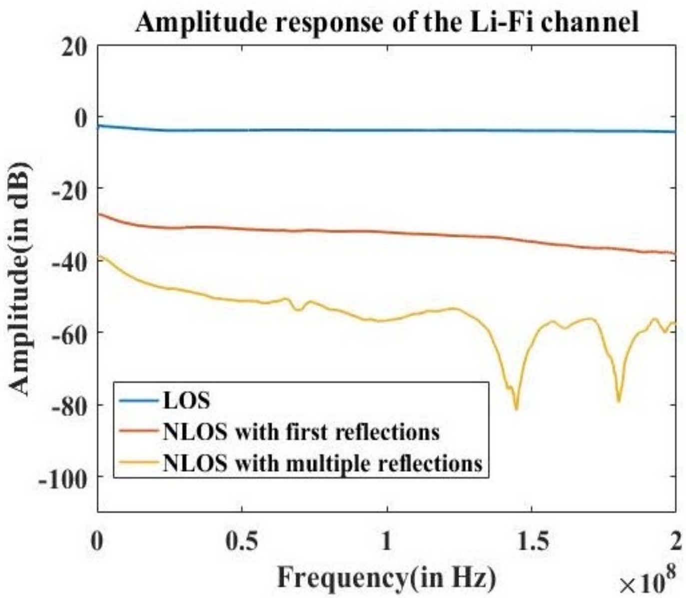


- **Direct link (LOS)**
  - high power
  - blocking is critical
  - no multipath
  - high bandwidth

- **Diffuse link (NLOS)**
  - low power
  - blocking is less relevant
  - inherent support for mobility
  - multipath → 1st order low pass, reduced bandwidth

LOS vs. diffuse





- **LOS is the dominant signal, if it is free**
  - high power and high bandwidth
- **First-order reflections**
  - 25 dB reduced power, rather high bandwidth
- **Higher-order reflections only**
  - 35 dB reduced power, lower bandwidth

Sreelal M. Mana et al, "Experiments in Non-Line-of-Sight Li-Fi Channels," *2019 Global LIFI Congress*, Paris, France, 2019

- Introduction
- What is LC?
- **Other LC standards**

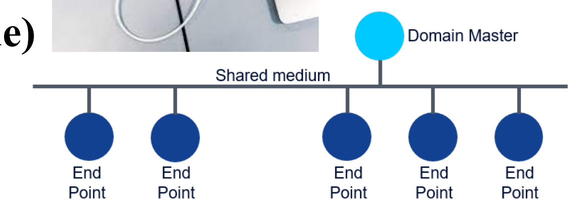
Other LC standards

- **IrDA – Infrared Data Association**
  - Founded 1993 to establish interoperable solution for infrared light data networking
  - Initial IrDA Data standard released in 1994 for P2P communications over IR light
  - Several amendments with bitrates to 1 Gb/s and providing broad application support

- **IEEE 802.15.7**
  - Task Group on Visible Light Communication established in Jan 2009
  - IEEE Std 802.15.7-2011, later revised to IEEE Std 802.15.7-2018
  - Now focusing on **Optical Camera Communication (OCC)**

- Introduction
- What is LC?
- **Other LC standards**

ITU-T G.9991



- **G.9991 is used for almost all LC products today**
- **Based on home networking standard G.996x (G.hn coax mode)**
  - chipsets from multiple vendors are available
- **Developed by ITU-T Q18/SG15: In-premises networking**
  - started 2015, first approval April 2019, latest update in April 2021
  - DCO-OFDM PHY, (DC biased Optical OFDM), adaptive bitloading, up to 2 Gbps
  - MAC (TDMA, CSMA) allows for Quality-of-Service through medium reservation for transmissions

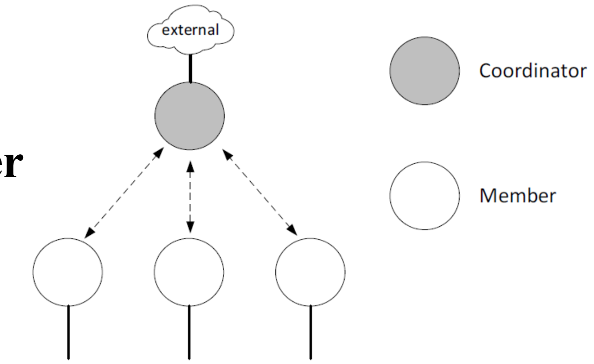
New LC standards address different markets

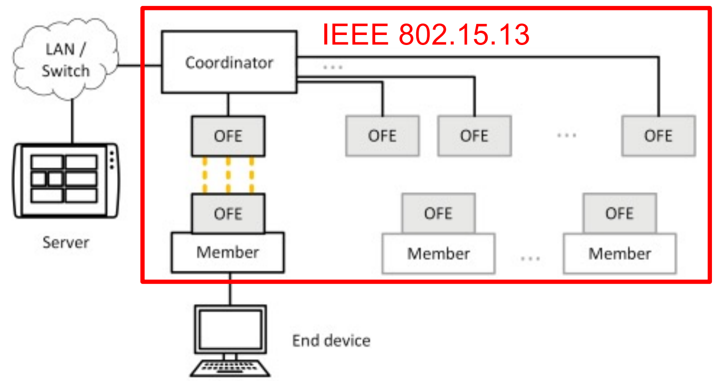
- **802.15.13**
  - high-end capabilities for industrial / medical / FWA markets
  - new features for increased range, higher reliability, deterministic latency
- **802.11bb**
  - capabilities address the consumer market
  - easy integration with commercially available chipsets, infrastructures and ecosystem

- **IEEE P802.15.13**
- Architecture & Service
- PHYs
- MAC
- Status

IEEE P802.15.13 - Overview

- **Focus: Industrial applications**
  - new standard including MAC and PHY
- **Goals: Simplicity, low implementation barrier**
  - simplified MAC
  - basic data transmission w/o security supported
  - two new PHYs
- **Star topology network**
  - coordinator manages the network
  - members associate with the network
  - allows P2MP or P2P communication
- **Interconnection with 802 LANs**





- IEEE P802.15.13
- **Architecture & Service**
- PHYs
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Architecture and service of 802.15.13

- **Data transmission always between Coordinator and Members**
  - Coordinator bridges data between two members
  - Only exception are relays
- **MAC Data interface**
  - EUI-48 addresses
  - Supports 802.1 MAC service
  - Shim not yet in 802.1AC (t.b.d.)

Table 13 Parameters of the MD-DATA.request primitive.

Name	Range	Description
DestinationAddress	MAC address	The destination address of the MSDU.
SourceAddress	MAC address	The source address of the MSDU.
Msdu	Octet Sequence	The MSDU in EtherType format, i.e., starting with the Length/Type field and ending with the MAC Client Data field as defined in IEEE Std 802.3™.
Priority	[0, 7]	The priority of the MSDU, as detailed in IEEE Std 802.1AC.
Acknowledged	TRUE, FALSE	Whether the associated MSDU is transmitted with acknowledgment request.

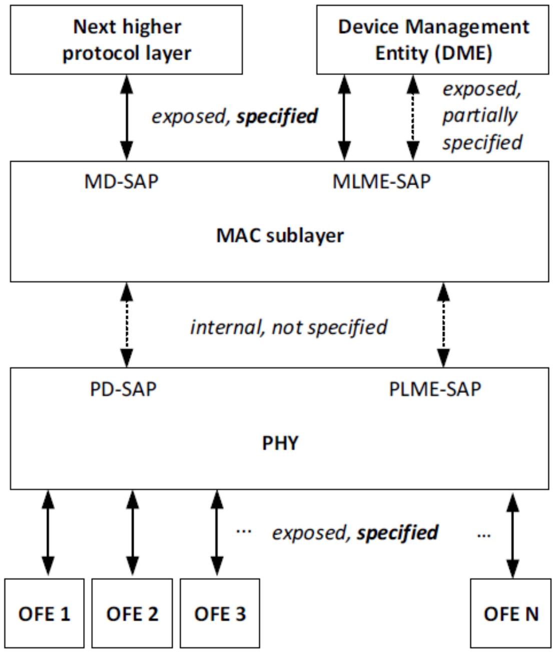
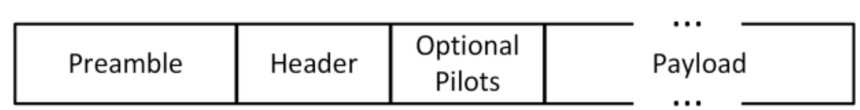


Figure 8 OWPAN device architecture.

- IEEE P802.15.13
- Architecture & Service
- **PHYs**
- MAC
- Status

Physical layers (PHYs)

- **Two physical layers (PHYs) with distinct properties**
  - OOK modulation → Energy efficiency
  - OFDM modulation → Spectral efficiency
- **Both support important features for LC:**
  - Bandwidth and rate adaptation to OFE and channel properties
  - MIMO pilots for channel estimation between multiple TX and RX
  - Cyclic prefix for frequency domain equalization
- **Both have similar Physical layer protocol data unit (PPDU) format:**
  - Preamble: for frame detection and channel estimation
  - Header: information about further PPDU structure
  - Optional pilots: for MIMO channel estimation
  - Payload: contains MAC data



- IEEE P802.15.13
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- **PHYs**
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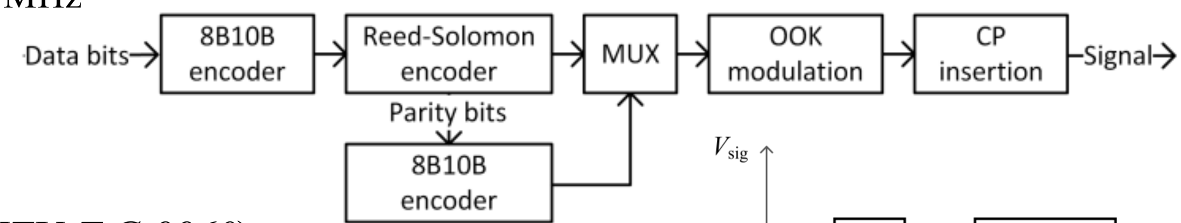
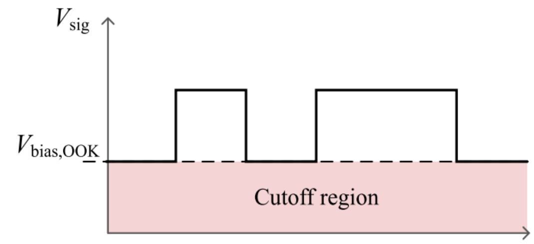
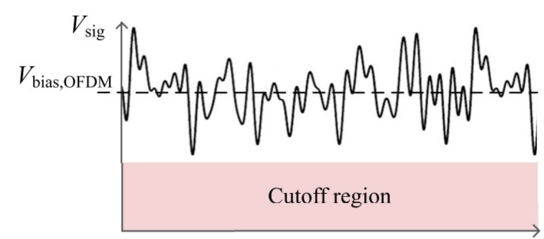
OOK & OFDM

- **OOK: „PM-PHY“**
  - Clock (symbol) rates 12.5 … 200 MHz
  - Reed-Solomon error coding
  - 8b10b line coding removes DC
  - Cyclic prefix 160 or 1280 ns
- **OFDM: „HB-PHY“** (*inspired by ITU-T G.9960*)
  - Bandwidths 50, 100 and 200 MHz
  - Adaptive bitloading → use optical frontend efficiently
  - LDPC encoding for high performance
  - Cyclic prefix: 160 to 1280 ns





M. Hinrichs *et al.*, "A Physical Layer for Low Power Optical Wireless Communications," in *IEEE Transactions on Green Communications and Networking*, vol. 5, no. 1, pp. 4-17.



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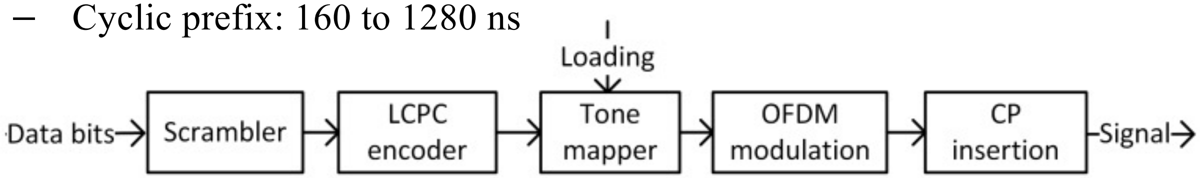

- IEEE P802.15.13
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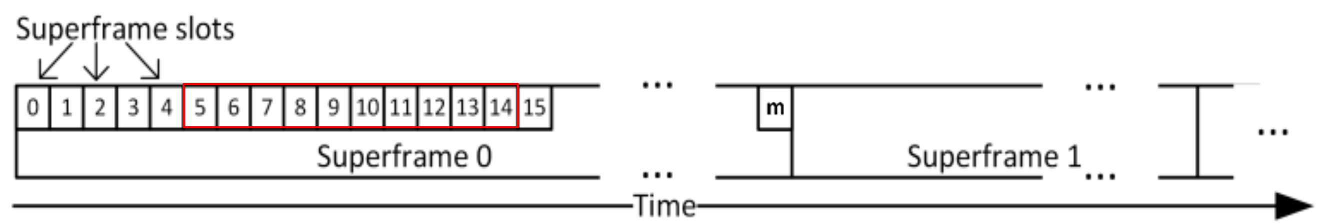
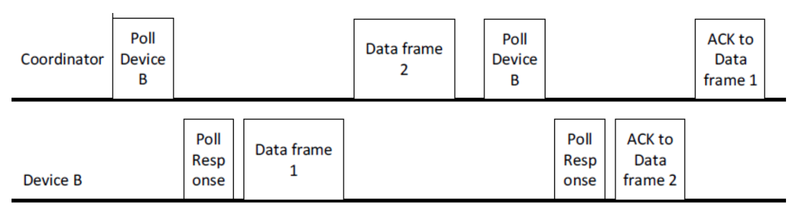
Channel access in 802.15.13

- **Two mechanisms: Scheduled & polled channel access**
- **Scheduled medium access – TDMA reservations without carrier sensing**
  - Random access & "guaranteed" access in *random time slices (RTS)* and *guaranteed time slices (GTS)*
  - Coordinator transmits control frames for synchronization and slice distribution regularly but in variable slot
  - Members transmit in allocated slices



- **Polled medium access (*based on IEEE 802.11 PCF*)**
  - Coordinator polls for random and dedicated transmissions
  - One (dedicated) or more (random) members transmit after receiving a poll frame



- IEEE P802.15.13
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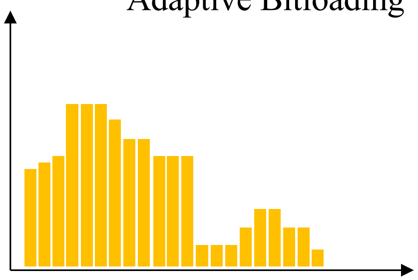
Other features in 802.15.13 MAC

- **Acknowledgment & Retransmission**
  - Single, Block ACK
  - Both not immediate due to possible fronthaul delay
- **PHY rate adaptation feedback**
  - MCS (=clock rate) selection for PM-PHY
  - Adaptive bitloading for HB-PHY
- **Fragmentation & Aggregation**
  - For efficient use of available resources
- **One general frame format (MPDU)**
  - Three frame types – *data*, *control*, *management*
  - Protocol information exchanged in „elements", that reside in MPDU payload

Adaptive Bitloading

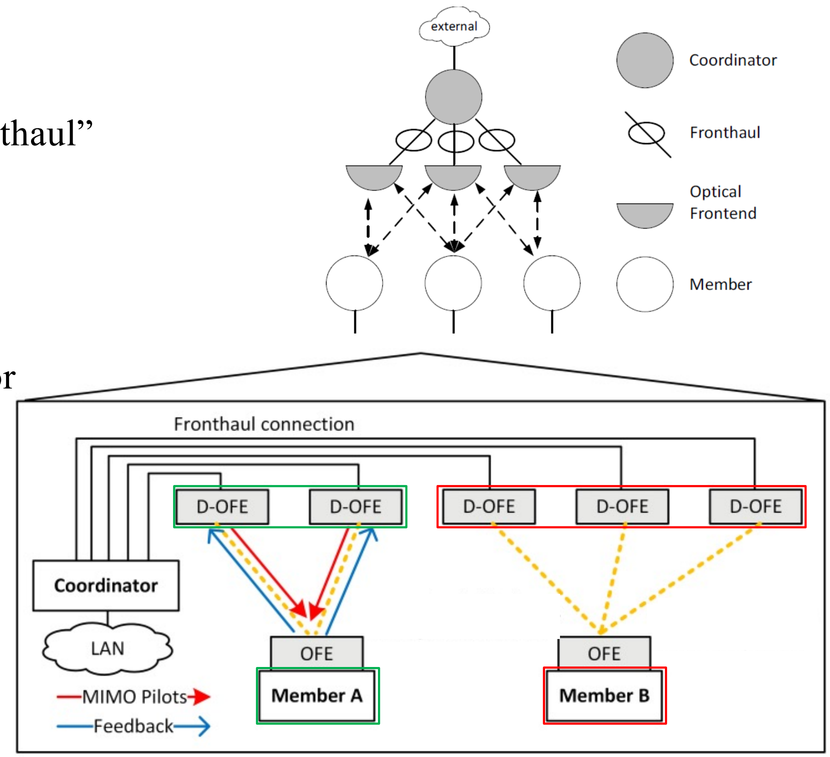


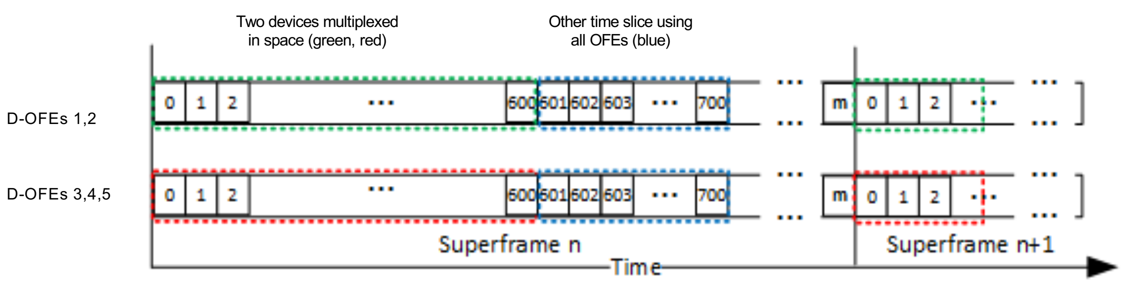
2 Octets	6 Octets	6 Octets	2 Octets	0/2 Octets	0/2 Octets	0/8 Octets	variable	4 Octets
Frame Control	Receiver Address	Transmitter Address	Payload Element ID	Sequence Control	Fragmentation Control	Relay Control	**Payload**	**FCS**
MAC header								

Distributed MIMO in 802.15.13

- IEEE P802.15.13
- Architecture & Service
- PHYs
- **MAC**
- Status

- **Multiple optical frontends (OFEs)**
  - <u>Spatial multiplexing</u> & <u>diversity</u> through MISO TX
  - Spatially distributed OFEs (D-OFE) connected via "fronthaul"
  - Fronthaul details are implementation-specific
- **MIMO Feedback routine for OFE selection**
  - Parallel transmission of orthogonal pilots from OFEs
  - CSI feedback of member's observed OFEs to coordinator
  - Coordinator schedules medium access based on CSI





- IEEE P802.15.13
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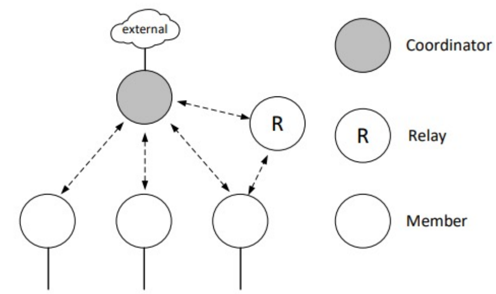
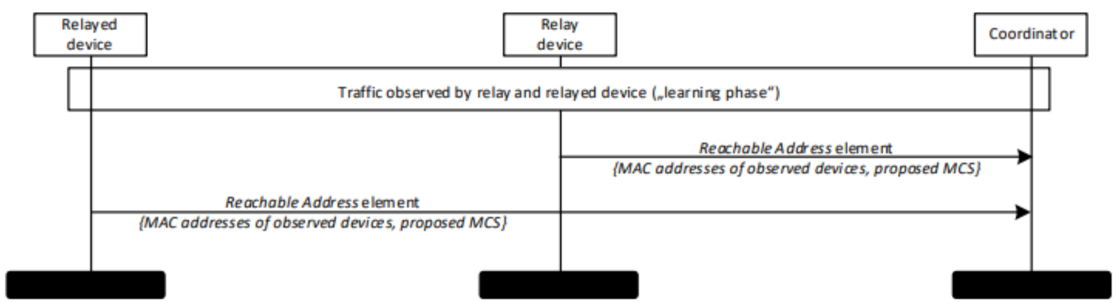
Relaying in 802.15.13

- **Make use of secondary light sources**
  - overcome LOS blocking, enhance the range
- **Relay selection**
  - relay and relayed device listen to the environment (learning)
  - report transmitter addresses of MPDUs to the coordinator
- **Significant gains up to 30 dB were observed**
  - suitable relay has a free LOS and it shortens the distance





- IEEE P802.15.13
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Implementation of 802.15.13

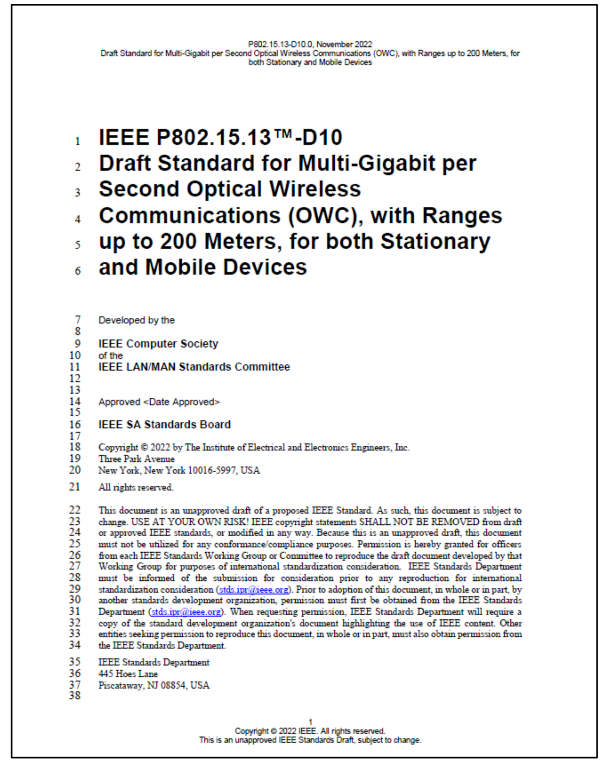
- **Validation through prototyping**
  - FPGA-based PHY implementation
  - MAC on general-purpose CPU
  - Bugs were found and fixed
- **Features**
  - PM-PHY is done, HB-PHY is in progress
  - Next: D-MIMO over Ethernet fronthaul, relaying
- **Test deployments**
  - in medical and industrial environments
  - projects LINCNET, 5G-COMPASS
- **Video about HILIGHT project available**
  - https://www.youtube.com/watch?v=NEWqi_QHUV8

P802.15.13 is finalized

- IEEE P802.15.13
- Architecture & Service
- PHYs
- MAC
- **Status**

- **Draft D10 is approved for publication by IEEE SA board**
- **Available in IEEExplore:**

  https://ieeexplore.ieee.org/document/9963940
- **Awaiting publication Q2-3/2023**



P802.15.13-D10.0, November 2022
Draft Standard for Multi-Gigabit per Second Optical Wireless Communications (OWC), with Ranges up to 200 Meters, for both Stationary and Mobile Devices

IEEE P802.15.13™-D10
Draft Standard for Multi-Gigabit per Second Optical Wireless Communications (OWC), with Ranges up to 200 Meters, for both Stationary and Mobile Devices

Developed by the

IEEE Computer Society
of the
IEEE LAN/MAN Standards Committee

Approved <Date Approved>

IEEE SA Standards Board

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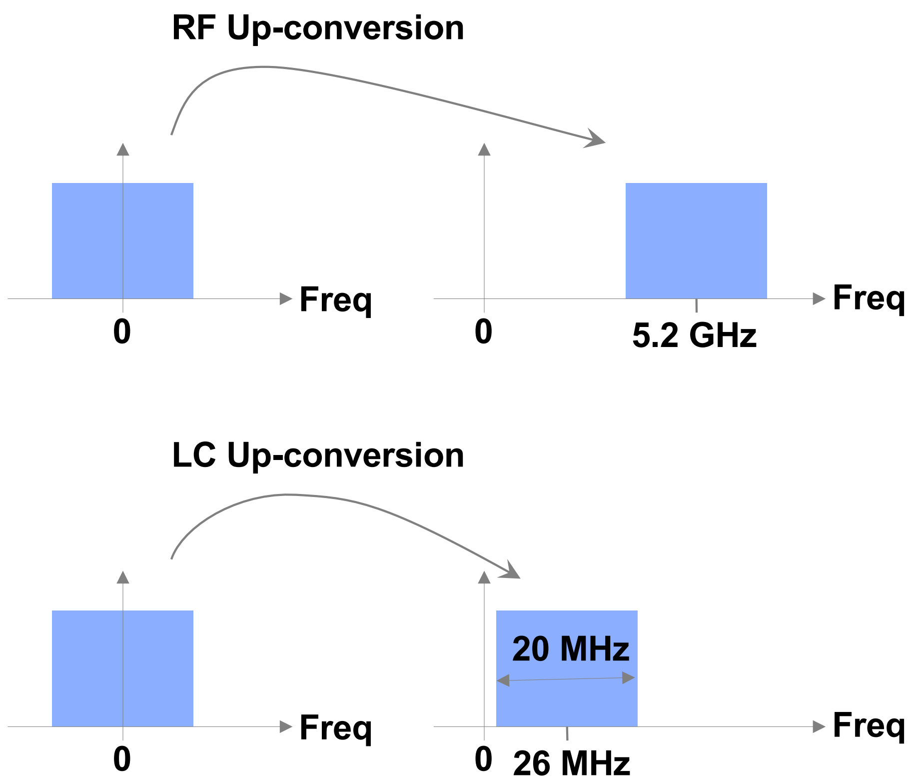
- **IEEE P802.11bb**
- PHY
- Status

IEEE 802.11bb overview

- **802.11bb aims at LC for the mass market**
- **IEEE 802.11 is the world's most common communications standard**
  - Over 3.8 billion Wi-Fi chipsets were shipped globally in 2021 in everything from smartphones, TVs, CCTV cameras, baby monitors, etc.
  - The large established market and open standards have created a highly competitive, vibrant ecosystem of devices, testing facilities, etc.
- **Deploying LC on a global scale requires reducing the barrier to entry for anyone looking to produce interoperable systems**
- **IEEE 802.11bb offers the simplest integration route with the highest number of possible device integration options**

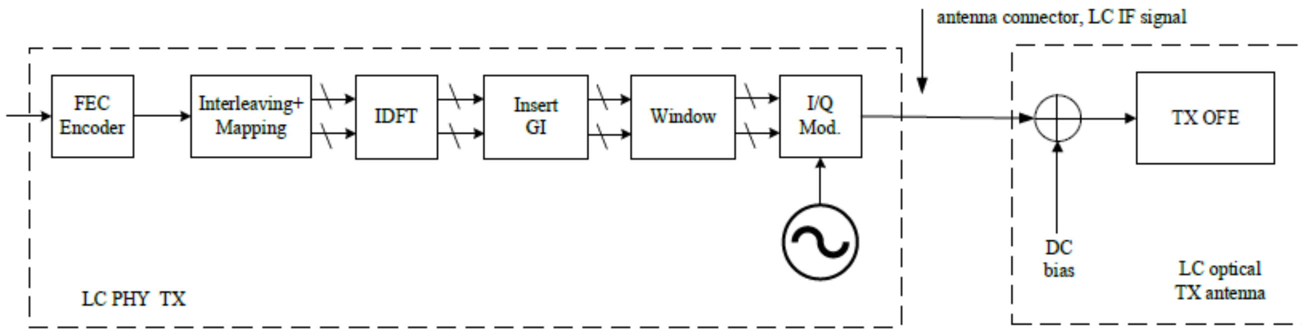
802.11bb PHY concept



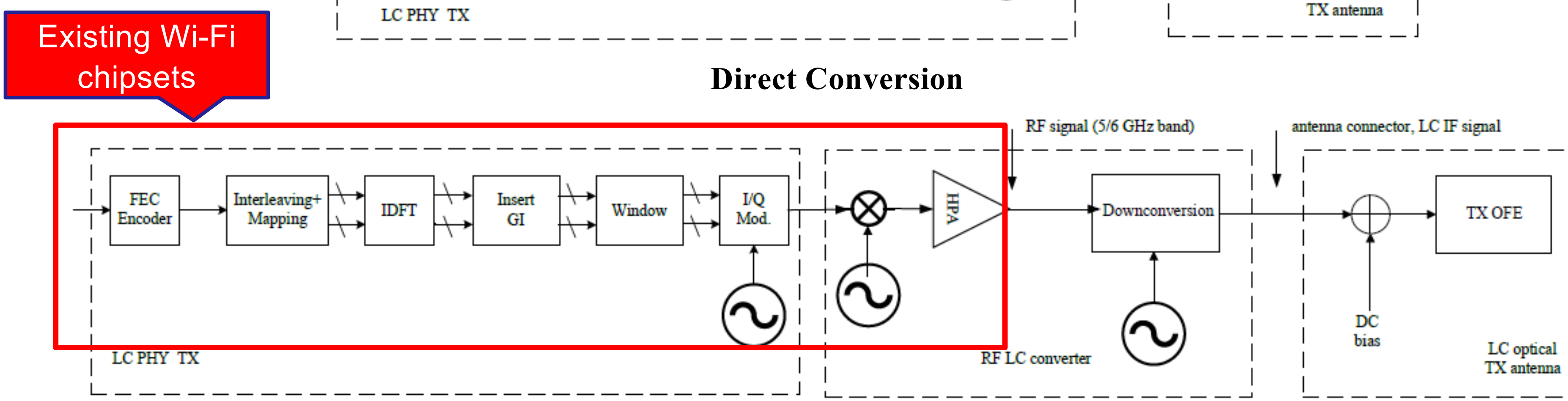
- **KISS approach: Reuse existing PHYs and MAC from 802.11**
  - RF frontend up-converts baseband signals onto e.g. 5.2 GHz
  - LC frontend up-converts baseband onto lower IF carrier frequency e.g. 26 MHz in the case of 20 MHz baseband signal
  - allows to convert any existing Wi-Fi chip solution into a LC solution through adding cheap circuitry
- **Same bitrates, same interfaces, same capabilities like Wi-Fi**

- IEEE P802.11bb
- **PHY**
- Status

PHY Implementation options



Direct Conversion



Up/Down Conversion from RF

LC IF mappings from 5 and 6 GHz

- IEEE P802.11bb
- **PHY**
- Status

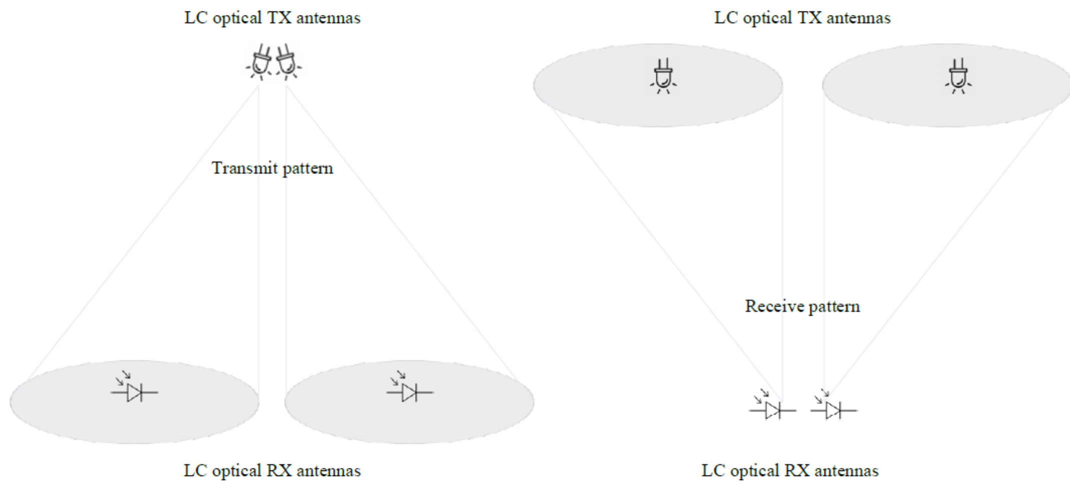
Table 31-1— RF to LC IF Mapping for channels in the 5 GHz and 6 GHz bands

Channel number	RF frequency band	RF center frequency (MHz)	LC IF center frequency (MHz)	Channel width: 20 MHz	40 MHz PrimaryChannel LowerBehaviour	40 MHz PrimaryChannel UpperBehaviour	40 MHz	80 MHz / 80+80 MHz	160 MHz
34		5170	16						
36		5180	26	Channel number 36 16 MHz-36 MHz					
38		5190	36		Channel number 36 16 MHz-56 MHz	Channel number 40 16 MHz-56 MHz			
40		5200	46	Channel number 40 36 MHz-56 MHz					
42		5210	56					Channel center frequency index 42 16 MHz-96 MHz	
44		5220	66	Channel number 44 56 MHz-76 MHz					
46		5230	76		Channel number 44 56 MHz-96 MHz	Channel number 48 56 MHz-96 MHz			
48		5240	86	Channel number 48 76 MHz-96 MHz					
50	5 GHz	5250	96				N.A.		Channel center frequency index 50 16 MHz-176 MHz
52		5260	106	Channel number 52 96 MHz-106 MHz					
54		5270	116		Channel number 52 96 MHz-136 MHz	Channel number 56 96 MHz-136 MHz			
56		5280	126	Channel number 56 116 MHz-136 MHz					
58		5290	136					Channel center frequency index 58 96 MHz-176 MHz	
60		5300	146	Channel number 60 136 MHz-156 MHz					
62		5310	156		Channel number 60 136 MHz-176 MHz	Channel number 64 136 MHz-176 MHz			
64		5320	166	Channel number 64 156 MHz-176 MHz					
			176						
1		5955	186	Channel number 1 176 MHz-196 MHz			Channel center frequency index 3 176 MHz-216 MHz		
3		5965	196						

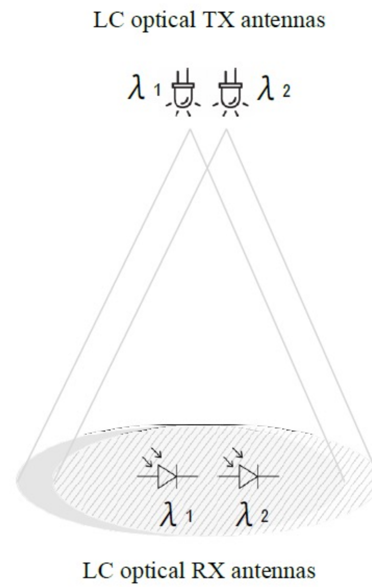
- **802.11bb channel mapping**
  - RF channels 1-64 with centre frequencies from 5.19-5.32 GHz as a block to LC IF centre frequencies 26-166 MHz
  - RF channels 1-64 with centre frequencies from 5.955-6.095 GHz as a block to LC IF centre frequencies 206-326 MHz

Spatial and wavelength multiplexing

- IEEE P802.11bb
- **PHY**
- Status



Spatial Multiplexing



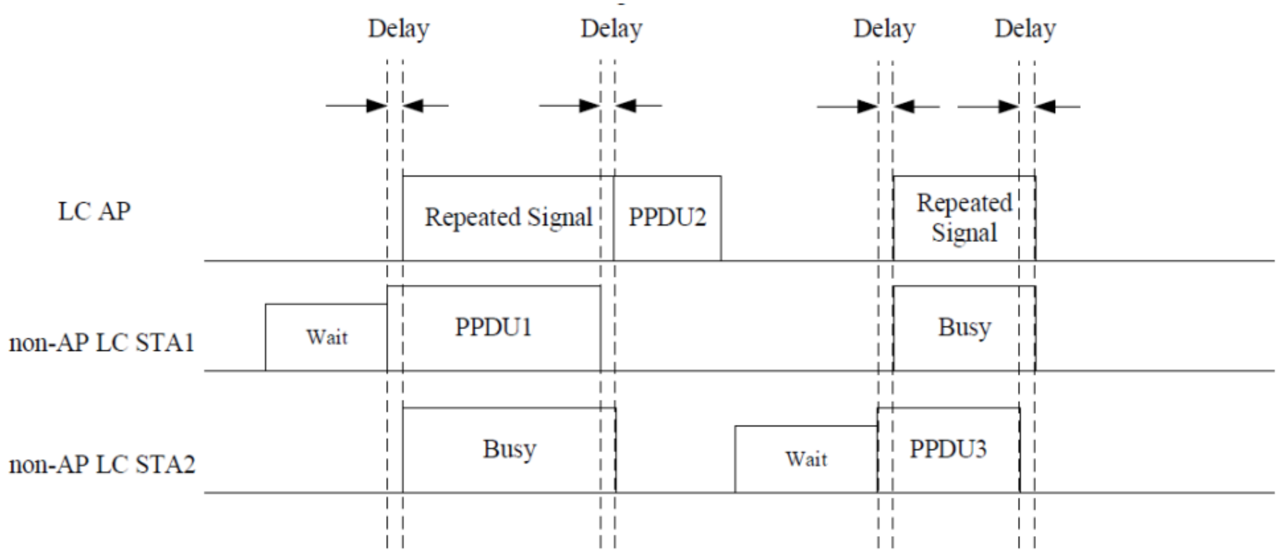
Wavelength Division Multiplexing

1) 800nm – 900nm
2) 900nm – 1000nm

CCA and LC repetition in 802.11bb

- IEEE P802.11bb
- **PHY**
- Status

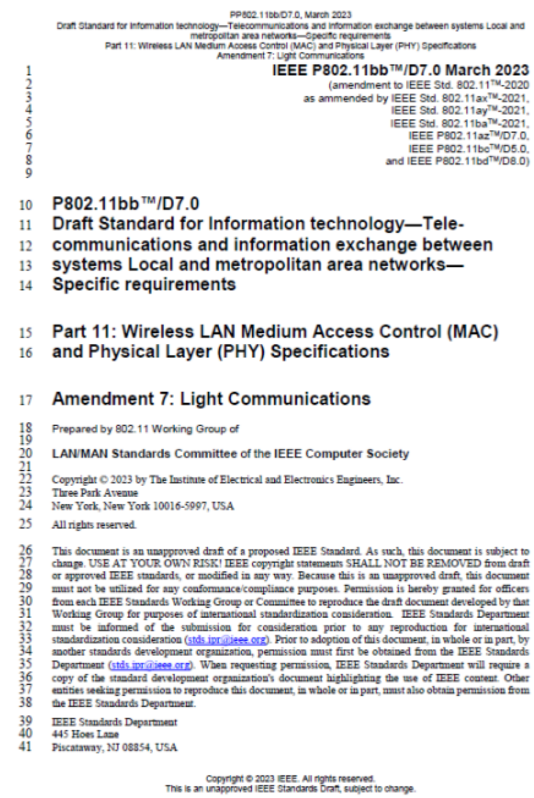
- **802.11bb systems shall have the same requirements for Clear Channel Assessment (CCA) as those for existing Wi-Fi 4, Wi-Fi 5 and Wi-Fi 6 chipsets**
- **802.11bb suggests an LC repetition approach where the LC AP immediately retransmits the received signal from a STA using amplify-and-forward as an example**



- IEEE P802.11bb
- PHY
- **Status**

P802.11bb is almost finalized

- **IEEE P802.11bb D6.0**
  - Approved with 96%
  - is available at the IEEE store https://ieeexplore.ieee.org/document/10042199
- **Draft 7.0 is currently in third IEEE SA recirculation ballot closing on 14 Mar**
  - Expected final 802.11 WG approval in Mar. 2023
  - Expected final 802 LMSC Approval in Mar. 2023
  - Expected RevCom & SA Board Approval by Jul. 2023



PP802.11bb/D7.0, March 2023
Draft Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements
Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications
Amendment 7: Light Communications

IEEE P802.11bb™/D7.0 March 2023
(amendment to IEEE Std. 802.11™-2020
as ammended by IEEE Std. 802.11ax™-2021,
IEEE Std. 802.11ay™-2021,
IEEE Std. 802.11ba™-2021,
IEEE P802.11az™/D7.0,
IEEE P802.11bc™/D5.0,
and IEEE P802.11bd™/D8.0)

P802.11bb™/D7.0
Draft Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements

Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications

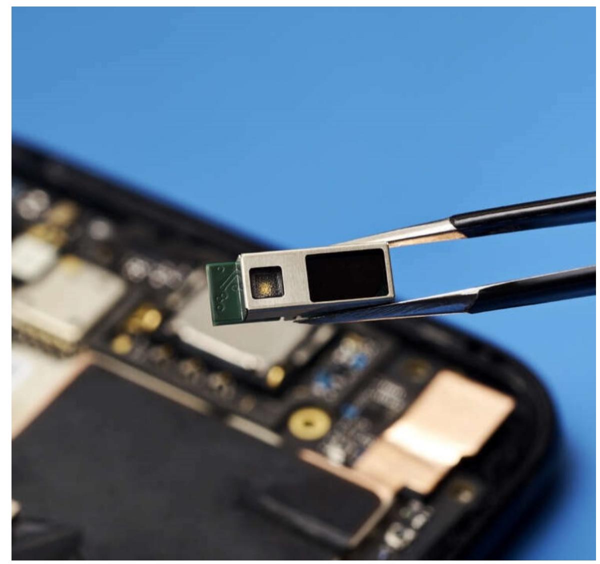
Amendment 7: Light Communications

Prepared by 802.11 Working Group of

LAN/MAN Standards Committee of the IEEE Computer Society

Mobile device integration

- **Video available**
  - https://vimeo.com/734356392
- **Minaturized optical antenna**
  - key for integration into mobile devices
  - multiple optical antennas needed
  - pointing into different directions
  - omnidirectional coverage enables mobility
- **Applications**
  - device-to-device (D2D) communication
  - short-range mobile access, e.g. to a desk light



Light Communications Alliance (LCA) in a nutshell

Formed in 2018

10

OUR FOCUS TECHNOLOGIES

- LiFi
- OCC
- FSO

MOTIVATION
Delivering the benefits of ubiquitous Light Communications to serve people & technologies, requires a far-reaching & coherent ecosystem working at a determined pace

MISSION
Driving a consistent, focused & concise approach to market education that will highlight the benefits, use cases & timelines for Light Communications

HOW
Aligning leaders across every industry to develop or envisage business models using Light Communication systems & technologies by defining a standard of education in an efficient communication & co-operation frame.

LCA

- IEEE P802.11bb
- PHY
- **Status**

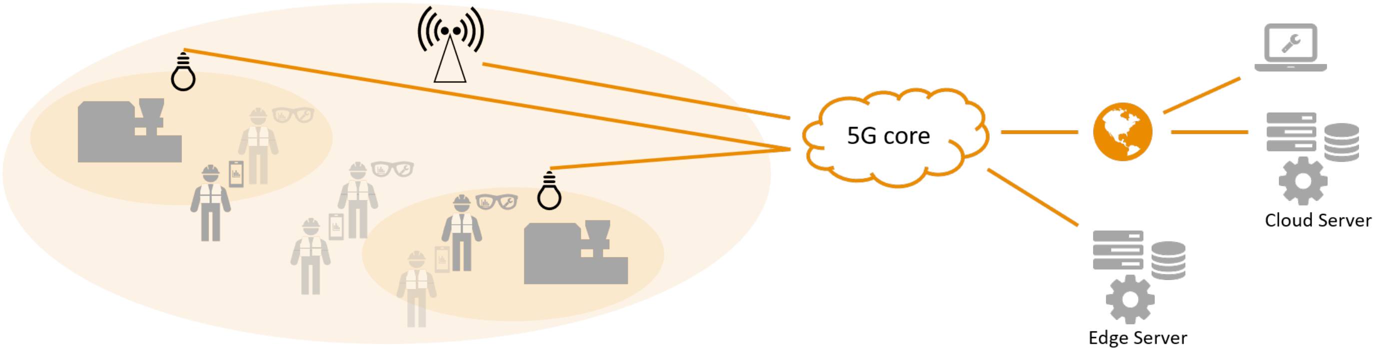
802.11bb Next steps

- **Support for continued education on the benefits of LC**
  - Consider joining the Light Communications Alliance
  - **http://lightcommunications.org/**
- **Enable Wi-Fi 7 support for LC**
- **Identify certification body for LC**
- **Define certification process**
- **Develop test specifications**

- **Technology demos**

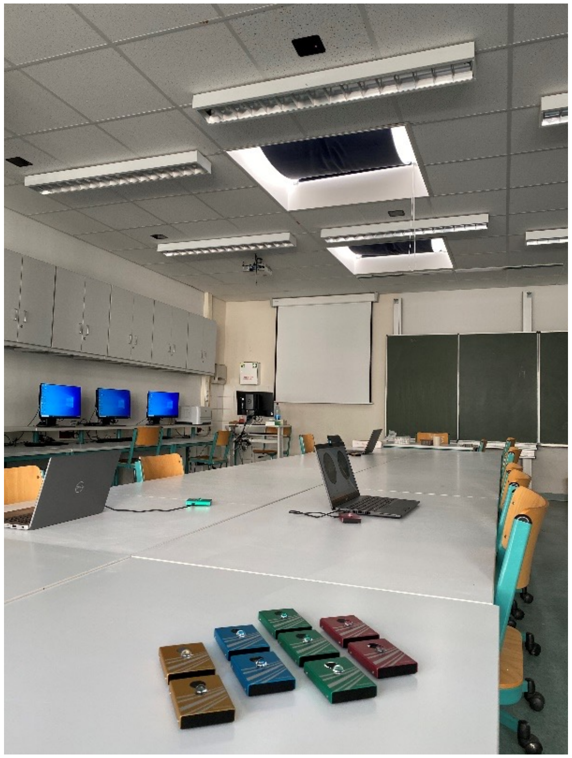
Industrial Communication

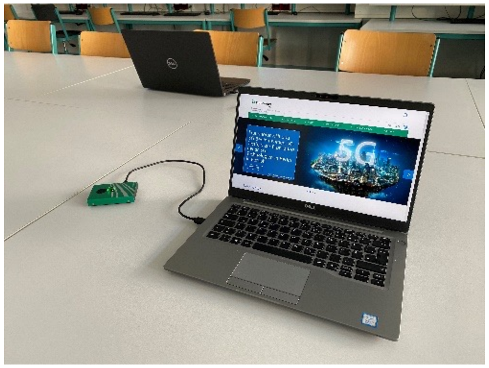
- **Video available**
  - **https://www.youtube.com/watch?v=tEJkIPv2KIA**
  - **00:30…02:49**
- **Integration of a distributed LC cell in 5G SA network**
  - via Non-3GPP Interworking Function (N3IWF)
  - seamless mobility between LiFi and 5G



Classrooms

- **Video available:**
  - https://www.youtube.com/watch?v=8KH6FHuVa6M
  - **00:00…03:00**
- **LC in a class room**
  - Multiple LC frontends at the ceiling next to luminaires
  - Dongles with USB-C interface
  - 1 Gbit/s DL, 100 Mbit/s UL





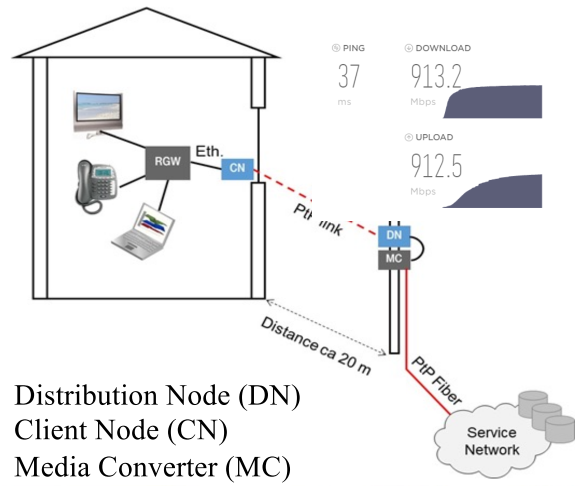
Residential

- **Video available**
  - **https://youtu.be/NbcmVXobGW0**
  - **00:00…01:30 and 02:24…04:25**
- **Living room covered by LC**
  - at KPN location in the harbor of Rotterdam/NL
  - large area coverage with Signify TrueLiFi
  - hotspot area covered by HHI Gbit LiFi link
- **Integration with other technologies**
  - powerline communication used as backhaul
  - handoff between Wi-Fi and LiFi

Fixed Wireless Access

- **Video available**
  - https://youtu.be/rpA9XrO2XqY
  - 00:31…04:22
- **Broadband access service via LC**
  - Wireless-to-the-Home (WttH)
- **Transmission through window glass**
  - RF is blocked, LC goes through
- **High quality FWA link**
  - 1 Gbit/s, < 1 ms latency, < 1 % loss
- **High reliability**
  - weather-independent performance
- **Applications**
  - high-speed Internet, video streaming

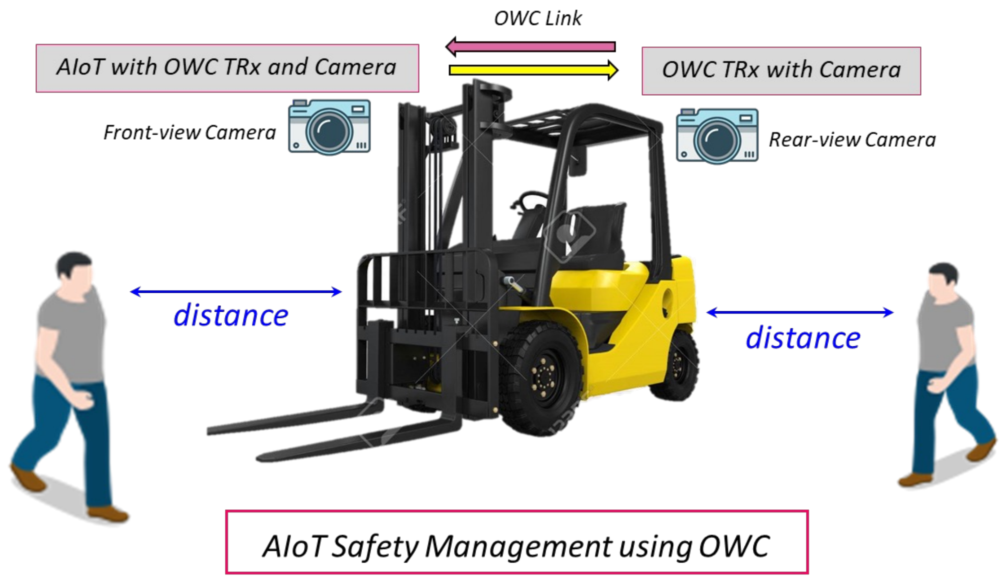
- **Technology demos**



- Technology demos

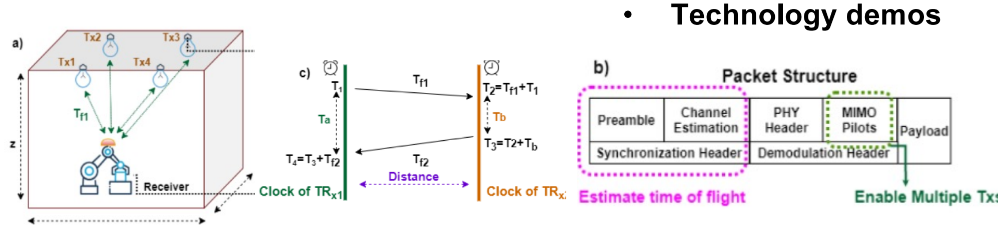
Industrial AIoT

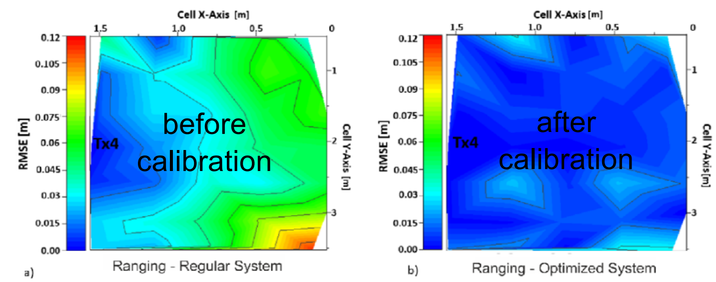
- **Video available**
  - https://etri.gov-dooray.com/mail/big-files/4663576d494c7333-255f35fc968ff277-306a05e75fec5df8-1870353be84
- **Safety management using LC**
  - two cameras estimate the distance of people moving around the forklift
  - one has Artificial Intelligence of Things (AIoT) functionality, the other has not
  - via LC, the other camera connects to AIoT
  - this way, a joint decision can be made and a security alert is issued in case of risk

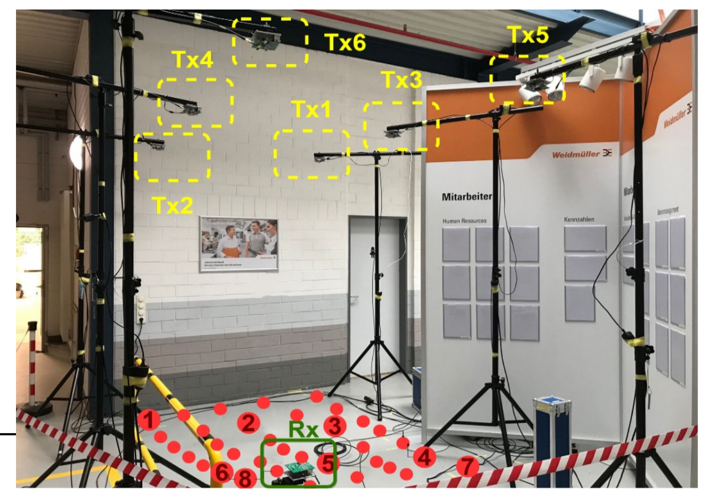


- Technology demos

Industrial Positioning







- **Video available**
  - **https://www.youtube.com/watch?v=tEJkIPv2KIA**
  - **00:31…01:21 and 02:10…03:25**
- **LC allows precise positioning**
  - LOS is primary propagation path → higher precision
  - measurements available in PHY (synch, MIMO pilots)
  - triangulation with distributed MIMO → 3D position
- **3 cm error in 3D is demonstrated**
  - after sophisticated calibration routine
  - near-realtime demonstration in Weidmüller factory
- **Applications**
  - „indoor GPS“ for automated guided vehicle (AGV)
  - aid artificial intelligence (AI) with context information

Summary

- **LC is promising in applications where RF is limited.**
  - Optical frontends use solid state lighting devices with driver and photodiodes with amplifier.
  - Light travels primarily through LOS, unlike RF.
- **IEEE 802 has developed two new standards for LC.**
  - 802.15.13 for industrial/medical applications
  - 802.11bb for residential/consumer applications.
- **Prototypes and early products are available for testing.**
  - fixed wireless access, industral communication and positioning, residential and home applications.
- **Proposed next step is hybrid integration of LC and RF.**

International efforts

- **A variety of projects has contributed to the development of light communication.**

H2020 WORTECS

Wireless Optical/Radio TErabit CommunicationS

https://wortecs.eurestools.eu/ (EU, 2017-20)

ELIOT

H2020 Enhance Lighting for the Internet of Things (EU, 2018-22)

https://www.eliot-h2020.eu/

5G CLARITY H2020 5G-CLARITY

Beyond 5G Multi-Tenant Private Networks Integrating Cellular, Wi-Fi, and LiFi, Powered by Artificial Intelligence and Intent Based Policy

https://www.5gclarity.com/ (EU, 2019-22)

Lincnet

LiFi-based 5G for industrial and medical networks (BMWK, 2022-24)

https://www.lincnet.de/en-gb

B5G OPEN H2020 B5G-OPEN

Beyond 5G – OPtical nEtwork coNtinuum

https://www.b5g-open.eu/ (EU, 2021-24)

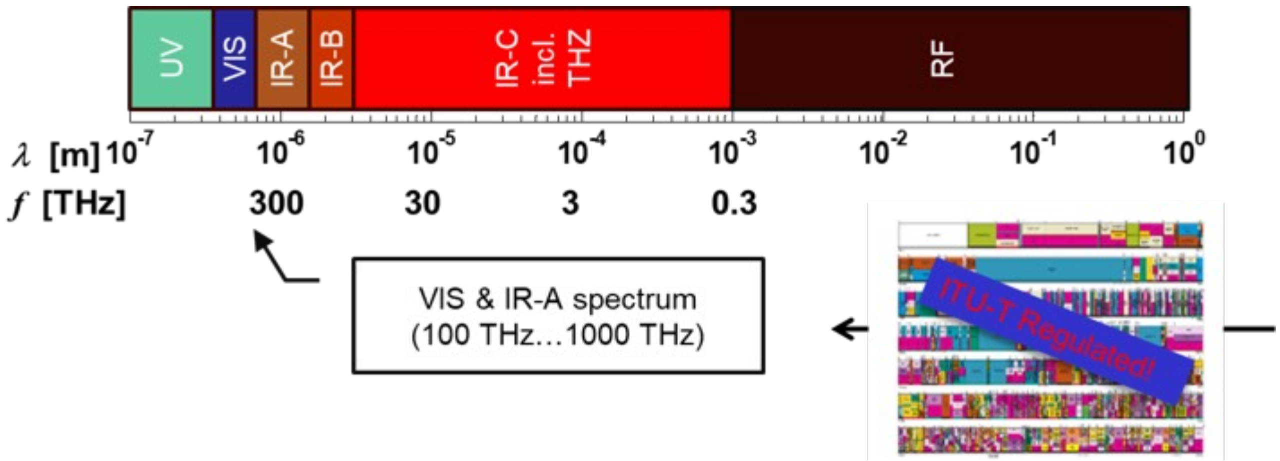
5G-COMPASS

Convergent Open Mobile and secure Provider-ASSisted 5G indoor and hotspot network

(BMDV, 2023-24)

Backup

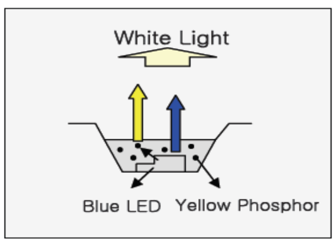
LC vs. RF

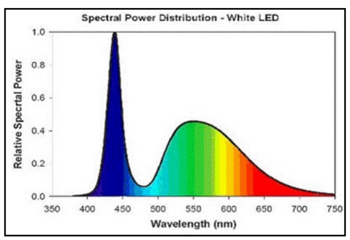


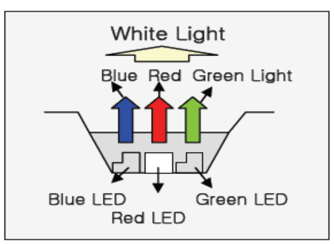
- Light spectrum is unregulated, similar like RF in ISM bands, limited by eye safety
- Communication is possible wherever the light goes
- LC has shorter range and is more directional than RF
- While RF often propagates via multi-path, light travels primarily via the LOS

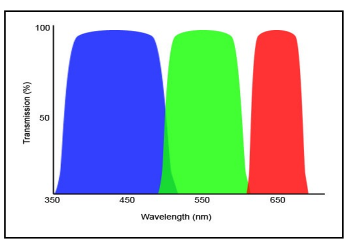
TX frontend: LEDs

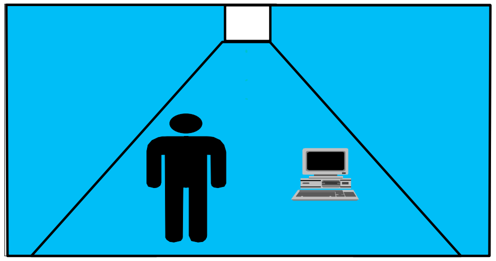
- **Low-cost high-power LEDs became available, e.g. for lighting**
- **For data transmission, LED can be modulated at high speed**
- **Flicker is invisible for the human eye**
- **Blue LED + phosphor**
  - blue LED is fast (~20 MHz)
  - phosphor is slow (1-2 MHz)
- **R+G+B type**
  - wavelength-division multiplexing (WDM → 802.11bb)
  - ~20 MHz per color
  - higher cost



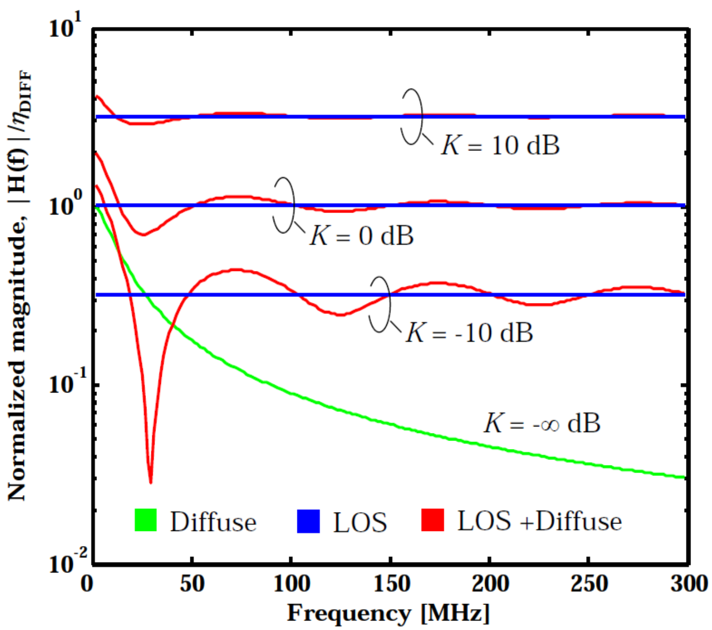








Directed and diffuse link



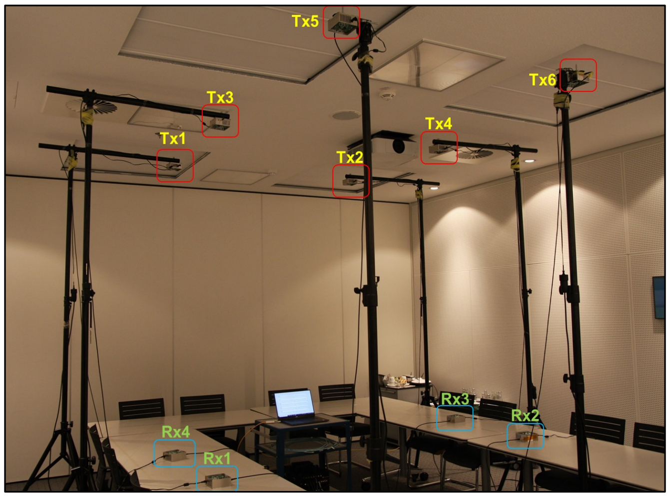
- **Channel response depends on**
  - Rice factor

$$K[\mathrm{dB}] = 20 \log \frac{\eta_{\mathrm{LOS}}}{\eta_{\mathrm{DIFF}}}$$

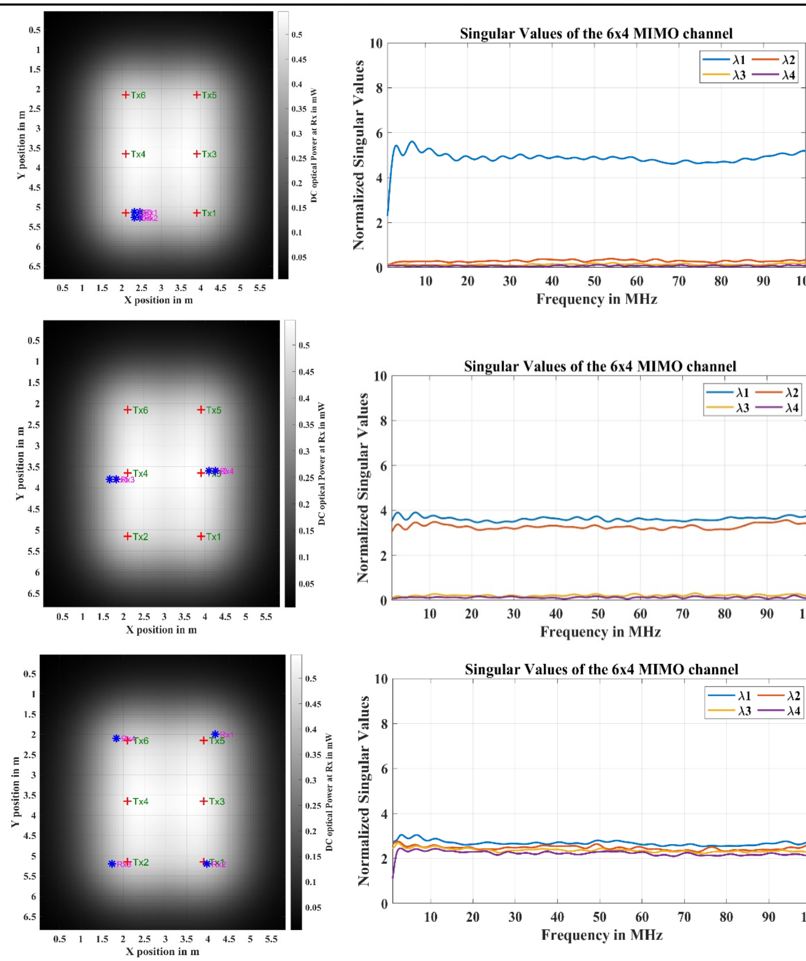
  - delay $\Delta\tau$ between direct and diffuse link

- **Compound channel is frequency-selective**
  - rare “fading” effects
  - when LOS and NLOS are similarly strong
  - in room corners, or when Tx and/or Rx are tilted

Distributed MIMO



- 6 optical frontends, 4 users
- can be considered as distributed MIMO
- measured with LC channel sounder
- channel rank depends on user location



Channel rank = 1

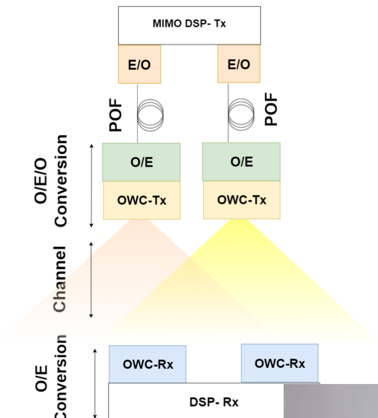
Channel rank = 2

Channel rank = 4

Sreelal M. Mana et al., "Distributed MIMO Experiments for LiFi in a Conference Room," *2020 12th CSNDSP*, Porto, Portugal, 2020

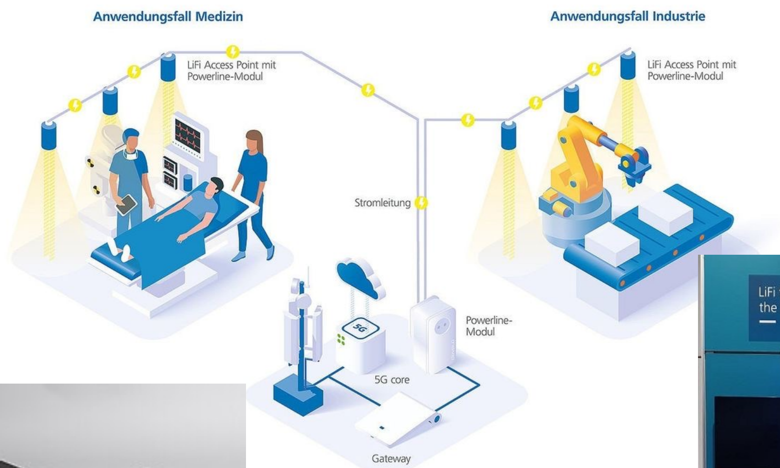
Fronthaul technologies for LC

Polymer Optical Fiber (POF)



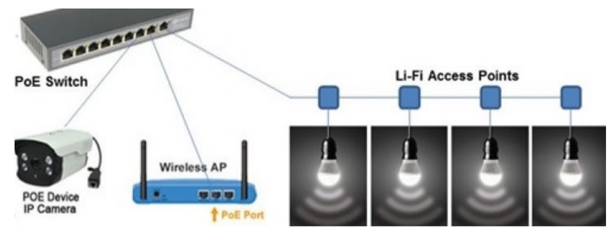
LC-over-POF
ECOC 2022
Fraunhofer-HHI

Powerline Communications (PLC)



LC-over-PLC
MWC 2023
Fraunhofer
HHI, devolo

Power-over-Ethernet (PoE)



LC-over-PoE
Signify 2021

How to encode over LC channel

- **LC is baseband channel, starting from DC up to some upper BW**
- **You and Kahn provided an upper bound on LC capacity (TMS bound)**

R. You and J. Kahn, „Upper-bounding the capacity of optical IM/DD Channels with multiple-subcarrier modulation and fixed bias using trigonometric moment space method“, IEEE Trans. Inf. Theory, Vol. 48, No. 2, Feb. 2002

- **Vucic provided a formula for TMS bound in frequency-selective LC channel**

J. Vucic, Ph.D. thesis, TU Berlin, 2009

$$C\left[\tfrac{\mathrm{bit}}{\mathrm{s}}\right] \le B_{\mathrm{SC}} \sum_{n=1}^{N_{\mathrm{opt}}} \log_2 \left(\underbrace{\frac{\eta^2 P_{\mathrm{O}}^2}{N_{\mathrm{D}}}}_{\gamma_n} H_n^2 \left(4 N_{\mathrm{opt}} 2^{\frac{1}{2N_{\mathrm{opt}}}} \right)^{-1} \right)$$

γ **effective SNR**

B_{SC} **subcarrier bandwidth**

$N_{\mathrm{opt}} \le N-1$ **optimal no. of carriers**

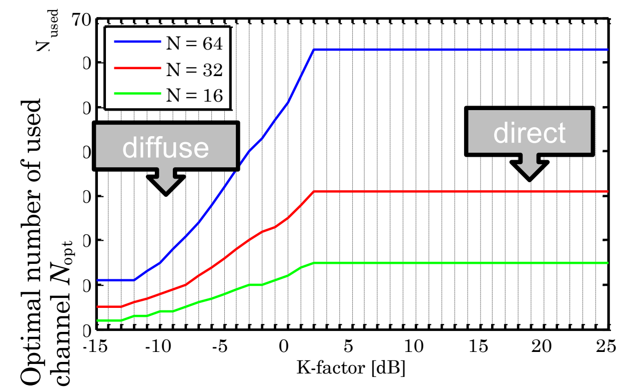
P_O **optical power**

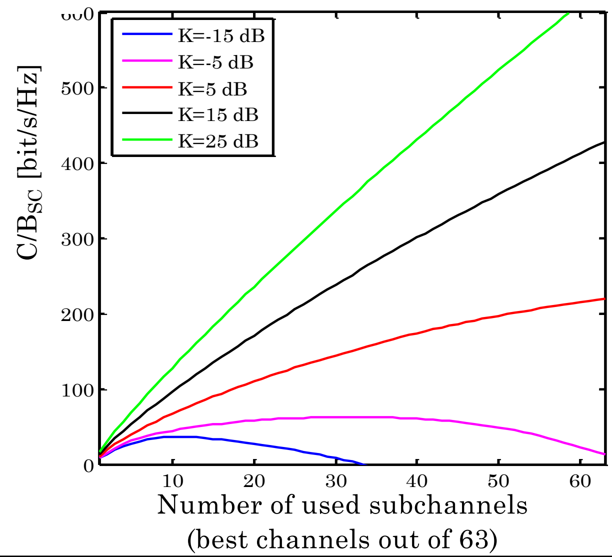
h **optical path gain**

N_D **detector noise**

Optimized TMS bound

- Maximize the bound using N_{opt}
- Diffused link: low-frequency subcarriers are used
- Direct link: all subcarriers are used



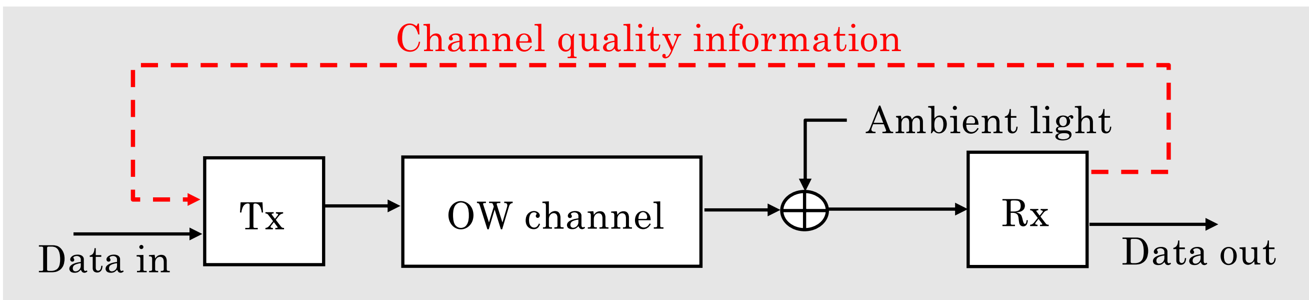


$B = 100$ MHz, $N - 1 = 63$,
$B_{SC} = B / N = \text{const.}$,
$P_O = 400\,\text{mW},\ \eta = 1$ A/W

Jelena Vucic, Ph.D. thesis, TU Berlin, 2009

Implementation

- **Mobile LC channel is frequency-selective and time variant**
- **Rate-adaptive approach based on feedback over the reverse link**

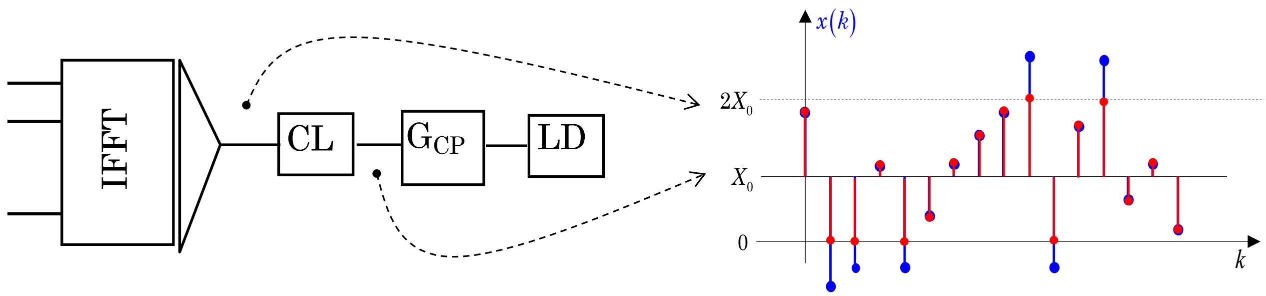


- **Compensation of channel dispersion effects**
  - Orthogonal frequency-division multiplex (OFDM)
  - Adaptive bitloading

J. Grubor et al. „Capacity Analysis in Wireless Infrared Communication using Adaptive Multiple Subcarrier Transmission, ICTON We C2.7, 2005.

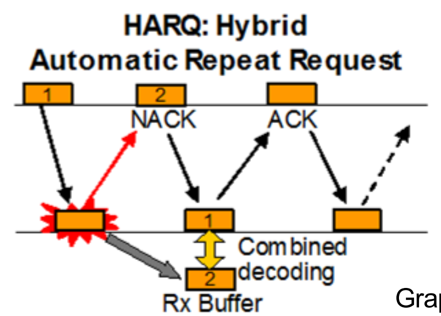
Controlled clipping

- **LC waveform is clipped below zero in the digital domain**



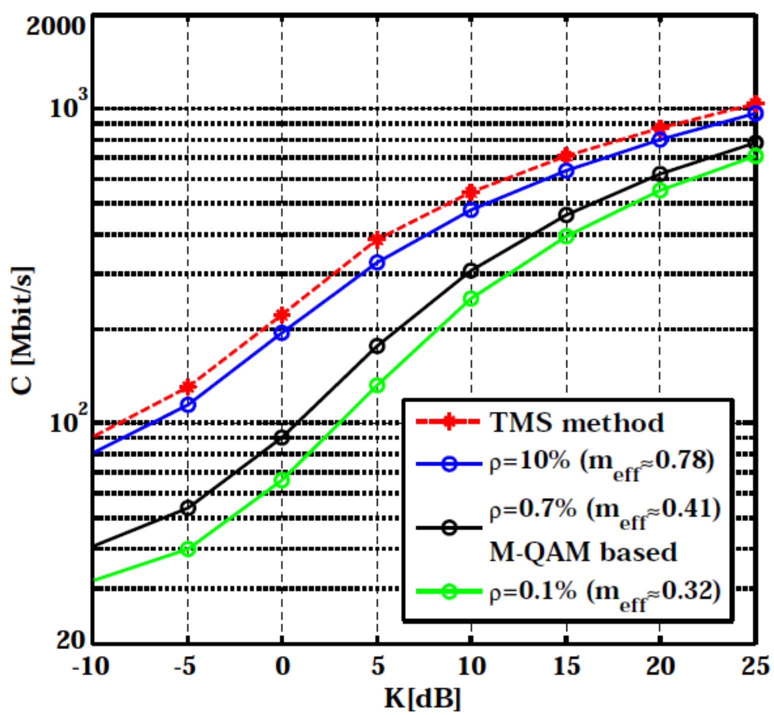
Jelena Vucic, Ph.D. thesis, TU Berlin, 2009

- **Clipping is tolerated while errors are corrected**
  - needs powerful forward error correction, such as LDPC
  - retransmissions (selective repeat)
- **Link adaptation with controlled clipping**
  - inner loop: adaptive bit-loading using fixed thresholds
  - outer-loop: adapt all bit-loading thresholds so that desired error rate is reached



Graph from NSN

Efficient coding over LC channels



P_{opt}=400 mW, h=1A/W, B=100 MHz, N=64

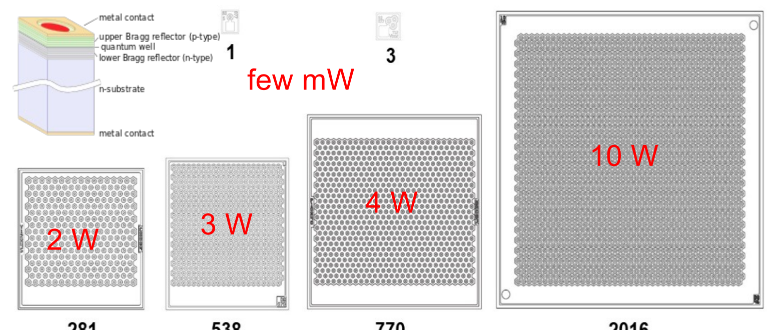
- Red is the upper bound using TMS
- DCO-OFDM with waterfilling
  - Green: Clipping is nearly avoided
  - Blue: 10% clipping probability
- Gap to the TMS bound is very small

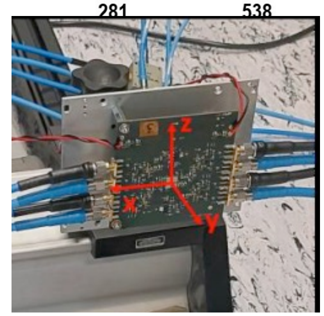
J. Vucic, Ph.D. thesis, TU Berlin, 2009

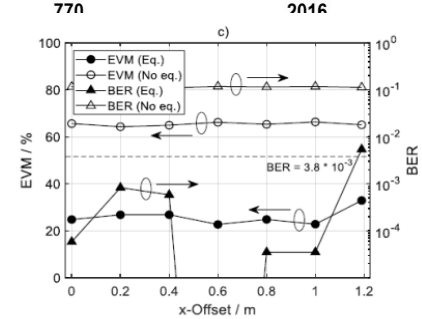
- DC-OFDM with waterfilling and controlled clipping is near to the TMS bound

VCSEL arrays: Bandwidth like mm-wave

- **Vertical cavity surface emitting laser (VCSEL)**
  - circular beam shape, few mW per VSEL
  - 20-30 GHz bandwidth for single VCSELs
- **VCSEL arrays**
  - 100s of VCSELs combined, parasitic L/C
  - similar area and beam shape like LED
- **Available for mass-market**
  - developed for LIDAR, also useful die LC
  - large VCSEL arrays still have few GHz BW
  - 2.5 Gbaud demonstrated in large coverage area

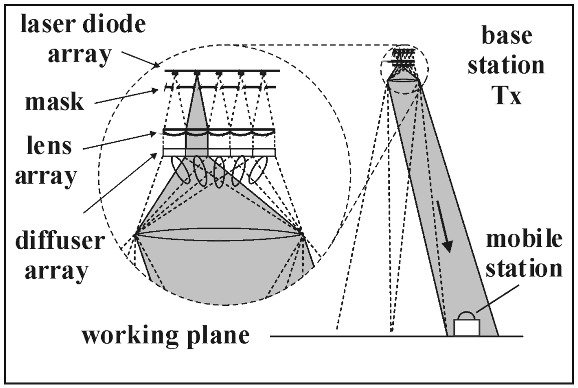


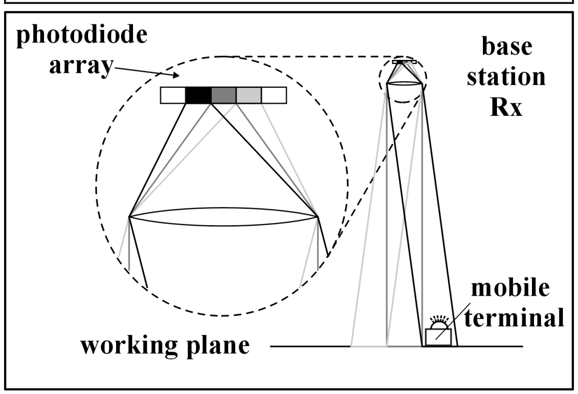




M. Hinrichs et al. Demonstration of 1.75 Gbit/s VCSEL-based Non-Directed Optical Wireless Communications with OOK and FDE ECOC 2022, paper We5.52

Future: Individually addressable arrays

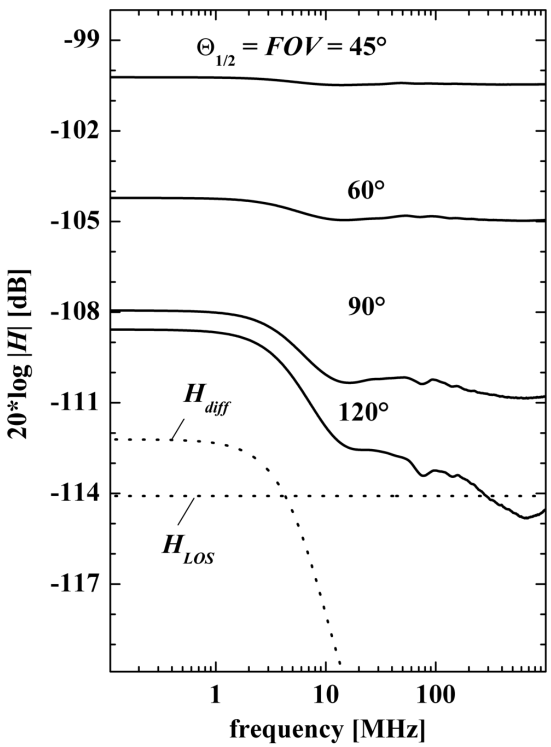




- **Select pixels in the TX array**
  - illuminate only the sector where the Rx is located
  - pixel groups: complexity vs. energy savings
  - higher bandwidth, use of drivers from fiber optics
- **Select pixels in the RX array**
  - smaller PD area = higher bandwidth
  - bootstrapping becomes obsolete → lower noise
  - spatially selective RX to suppress unwanted interference
  - from ambient light or other mobile devices
  - spatial multiplexing

V. Jungnickel et al., Electronic Tracking for Wireless Infrared Communications, IEEE Trans. Wireless Commun., Vol. 2, No. 5, Sept. 2003

Impact of arrays



- **Shown results are for critical scenario**
  - LOS signal is increased
  - NLOS signal is reduced
- **RX power and bandwidth are increased**
- **Moderate sector sizes will be enough**
  - No need for pencil beams

V, Jungnickel et al., Electronic Tracking for Wireless Infrared Communications, IEEE Trans. Wireless Commun., Vol. 2, No. 5, Sept. 2003