IEEE 802 Standards on Light Communication

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</tbody>
</table>
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
LC is useful where RF has limitations

<table>
<thead>
<tr>
<th>Defence &amp; Environment</th>
<th>Data &amp; Industrial</th>
<th>Office &amp; Commercial</th>
<th>Retail &amp; Financial</th>
<th>Smart City &amp; Transport</th>
<th>Consumer &amp; Lifestyle</th>
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<tbody>
<tr>
<td>Field command</td>
<td>Data centres</td>
<td>Smart building</td>
<td>Indoor location</td>
<td>Smart city</td>
<td>Mobile devices</td>
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<td>Secure comms</td>
<td>Industry 4.0</td>
<td>Secure comms</td>
<td>Shop analytics</td>
<td>Smart transport</td>
<td>Smart home</td>
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<td>Harsh enviro</td>
<td>IoT sensors</td>
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<td>Underwater</td>
<td>Safe enviro</td>
<td>Net offload</td>
<td>Back office</td>
<td>Backhaul</td>
<td>Lighting</td>
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</tbody>
</table>

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

Differences types of light communications have different applications.

- **OCC (Optical Camera Communications)**
  - Low Speed
  - Geo Location
  - Advertisements
  - Notifications

- **LiFi (Light Fidelity)**
  - Secure high-speed mobile wireless communications

- **FSO (Free Space Optics)**
  - 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

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.

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

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

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Light propagation

- **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 $\rightarrow$ 1st order low pass, reduced bandwidth

BS: base station, MS: mobile station

$ h(t) $
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

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)**
• **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 - 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**
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.

<table>
<thead>
<tr>
<th>Name</th>
<th>Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DestinationAddress</td>
<td>MAC address</td>
<td>The destination address of the MSDU.</td>
</tr>
<tr>
<td>SourceAddress</td>
<td>MAC address</td>
<td>The source address of the MSDU.</td>
</tr>
<tr>
<td>Msdu</td>
<td>Octet Sequence</td>
<td>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™.</td>
</tr>
<tr>
<td>Priority</td>
<td>[0, 7]</td>
<td>The priority of the MSDU, as detailed in IEEE Std 802.1AC.</td>
</tr>
<tr>
<td>Acknowledged</td>
<td>TRUE, FALSE</td>
<td>Whether the associated MSDU is transmitted with acknowledgment request.</td>
</tr>
</tbody>
</table>

Figure 8 OWPAN device architecture.
Physical layers (PHYs)

- Two physical layers (PHYs) with distinct properties
  -OOK modulation $\rightarrow$ Energy efficiency
  -OFDM modulation $\rightarrow$ 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

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Header</th>
<th>Optional Pilots</th>
<th>...</th>
<th>Payload</th>
</tr>
</thead>
</table>

...
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

![Diagram of OOK & OFDM system]
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
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
Distributed MIMO in 802.15.13

- **Multiple optical frontends (OFEs)**
  - Spatial multiplexing & diversity 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
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
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_QHUy8
P802.15.13 is finalized

- Draft D10 is approved for publication by IEEE SA board
- Awaiting publication Q2-3/2023
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**
PHY Implementation options

- IEEE P802.11bb
- PHY
- Status

Direct Conversion

Up/Down Conversion from RF

Existing Wi-Fi chipsets
### LC IF mappings from 5 and 6 GHz

**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

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

<table>
<thead>
<tr>
<th>Channel number</th>
<th>RF center frequency (MHz)</th>
<th>LC IF center frequency (MHz)</th>
<th>20 MHz Primary Channel Lower/Spectrum</th>
<th>40 MHz Primary Channel Lower/Spectrum</th>
<th>40 MHz Upper/Spectrum</th>
<th>80-86 MHz</th>
<th>100 MHz</th>
</tr>
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<tbody>
<tr>
<td>36</td>
<td>5190</td>
<td>Channel number 36</td>
<td>10 MHz-30 MHz</td>
<td>Channel number 36</td>
<td>10 MHz-30 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>5200</td>
<td>Channel number 38</td>
<td>10 MHz-30 MHz</td>
<td>Channel number 38</td>
<td>10 MHz-30 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>5210</td>
<td>Channel number 40</td>
<td>10 MHz-30 MHz</td>
<td>Channel number 40</td>
<td>10 MHz-30 MHz</td>
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<td>42</td>
<td>5220</td>
<td>Channel number 42</td>
<td>50 MHz-70 MHz</td>
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<td>44</td>
<td>5230</td>
<td>Channel number 44</td>
<td>50 MHz-70 MHz</td>
<td>Channel number 44</td>
<td>50 MHz-70 MHz</td>
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<td>5240</td>
<td>Channel number 46</td>
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<td>Channel number 46</td>
<td>70 MHz-90 MHz</td>
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<td>Channel number 54</td>
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<td>56</td>
<td>5290</td>
<td>Channel number 56</td>
<td>130 MHz-170 MHz</td>
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<td>130 MHz-170 MHz</td>
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<td>5300</td>
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<td>230 MHz-270 MHz</td>
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<td>5350</td>
<td>Channel number 68</td>
<td>250 MHz-290 MHz</td>
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<td>250 MHz-290 MHz</td>
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<td>70</td>
<td>5360</td>
<td>Channel number 70</td>
<td>270 MHz-310 MHz</td>
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<td>270 MHz-310 MHz</td>
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<td>370 MHz-410 MHz</td>
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<td>Channel number 82</td>
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<td>92</td>
<td>5470</td>
<td>Channel number 92</td>
<td>490 MHz-530 MHz</td>
<td>Channel number 92</td>
<td>490 MHz-530 MHz</td>
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<td></td>
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<tr>
<td>94</td>
<td>5480</td>
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<td>510 MHz-550 MHz</td>
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<td>96</td>
<td>5490</td>
<td>Channel number 96</td>
<td>530 MHz-570 MHz</td>
<td>Channel number 96</td>
<td>530 MHz-570 MHz</td>
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<tr>
<td>98</td>
<td>5500</td>
<td>Channel number 98</td>
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<td>Channel number 98</td>
<td>550 MHz-590 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>5510</td>
<td>Channel number 100</td>
<td>570 MHz-610 MHz</td>
<td>Channel number 100</td>
<td>570 MHz-610 MHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**IEE P802.11bb**

**PHY**

**Status**
Spatial and wavelength multiplexing

Spatial Multiplexing

Wavelength Division Multiplexing
1) 800nm – 900nm
2) 900nm – 1000nm
CCA and LC repetition in 802.11bb

- 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
P802.11bb is almost finalized

- **IEEE P802.11bb D6.0**
  - Approved with 96%

- **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
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

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.
802.11bb Next steps

- **Support for continued education on the benefits of LC**
  - Consider joining the Light Communications Alliance
  - [http://lightcommunications.org/](http://lightcommunications.org/)

- **Enable Wi-Fi 7 support for LC**

- **Identify certification body for LC**

- **Define certification process**

- **Develop test specifications**
Industrial Communication

- Video available
  - [https://www.youtube.com/watch?v=tEJkIPv2KIA](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](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](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
Industrial AIoT

- **Video available**
  - [https://etri.gov-dooray.com/mail/big-files/4663576d494c7333-255f35fc968ff277-306a05e75fec5df8-1870353be84](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
Industrial Positioning

- **Video available**
  - [https://www.youtube.com/watch?v=tEJkIPv2KIA](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, industrial 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.

- **LiFi-based 5G for industrial and medical networks (BMWK, 2022-24)**
  - [https://www.lincnet.de/en-gb](https://www.lincnet.de/en-gb)

- **H2020 WORTECS**
  - Wireless Optical/Radio Terabit Communication
  - [https://wortecs.eurestools.eu](https://wortecs.eurestools.eu) (EU, 2017-20)

- **ELIOT**
  - H2020 Enhance Lighting for the Internet of Things (EU, 2018-22)
  - [https://www.eliot-h2020.eu](https://www.eliot-h2020.eu)

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

- **H2020 B5G-OPEN**
  - Beyond 5G – OPTical nEtwork coNtinuum
  - [https://www.b5g-open.eu](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
• 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
    \[ K[\text{dB}] = 20 \log \frac{\eta_{\text{LOS}}}{\eta_{\text{DIFF}}} \]
  - 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

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)  Powerline Communications (PLC)  Power-over-Ethernet (PoE)

LC-over-POF  
ECOC 2022  
Fraunhofer-HHI

LC-over-PLC  
MWC 2023  
Fraunhofer HHI, devolo

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)

  \[ C_{\text{bit/s}} \leq B_{SC} \sum_{n=1}^{N_{\text{opt}}} \log_2 \left( \frac{\eta^2 P_O^2}{N_{D} H_n^2} \left( 4 N_{\text{opt}} 2^{\frac{1}{2 N_{\text{opt}}}} \right)^{-1} \right) \]

  \[ \gamma_n \]

  \[ \gamma \] effective SNR

  \[ B_{SC} \] subcarrier bandwidth

  \[ N_{\text{opt}} \leq N - 1 \] optimal no. of carriers

  \[ P_O \] optical power

  \[ h \] optical path gain

  \[ N_D \] detector noise


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

Optimized TMS bound

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

\[ B = 100 \text{ MHz}, \quad N - 1 = 63, \]
\[ B_{\text{sc}} = B / N = \text{const.}, \]
\[ P_0 = 400 \text{ mW}, \quad \eta = 1 \text{ A/W} \]

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

Controlled clipping

- LC waveform is clipped below zero in the digital domain

- 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

Efficient coding over LC channels

- **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**


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

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

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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 $\rightarrow$ lower noise
  - spatially selective RX to suppress unwanted interference
  - from ambient light or other mobile devices
  - spatial multiplexing

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