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WHITE PAPER

HIGH DATA RATE LIGHT COMMUNICATION STANDARDS OF IEEE 802 STANDARDS COMMITTEE

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IEEE 802 LAN MAN Standards Committee recently finalized its work on two standards for light communications (LC). IEEE 802.15.13-2023 Standard for Multi-Gigabit per Second Optical Wireless Communications (OWC), with Ranges up to 200 meters, for both stationary and mobile devices (IEEE 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 IEEE P802.11bb 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 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.

Abstract

In this white paper we present major use cases and overview of the standards. Before providing the details of use cases, we would like to state some of the benefits of light communications.

Security: LC technology is more secure than radio frequency (RF) communication, as it cannot penetrate walls or other obstacles, making it difficult to intercept the signal.
Immunity to Radio Interference: LC technology is immune to electromagnetic interference (EMI), which can interfere with RF communication, making it a reliable communication option in environments with high levels of EMI.
Safety: LC equipment does not create same levels of EMI, thus safe to use around sensitive equipment.

Usage Models for Light Communications

IEEE 802.11bb Group 4 main usage models for light communications (LC) [1].

The below terminology is used to explain the usage models:

Usage Model – A usage model is the combination of all the things below; not to be confused with a use case which is the specific set of steps to accomplish a particular task.

Pre-Conditions – Initial conditions before the use case begins.

Environment – The type of place in which the network of the use case is deployed, such as home, outdoor, hot spot, enterprise, metropolitan area, etc.

Application – A source and/or sink of wireless data that relates to a particular type of user activity. Examples are streaming video and VoIP.

Traffic Conditions – General background traffic or interference that is expected while the use case steps are occurring. Overlapping BSSs (OBSSs), existing video streams, and interference from cordless phones are all examples of traffic conditions.

Use Case – A use case is task oriented. It describes the specific step-by-step actions performed by a user or device. One use case example is a user starting and stopping a video stream.

Usage Model 1 Industrial Wireless

Pre-Conditions
Devices may experience unstable radio frequency (RF) connection due to Electro-Magnetic Interference (EMI) in factories. LC is deployed to provide reliable wireless connectivity for industrial wireless networks.

Environment
All communications are within a large metal building, industrial or automated work cell. The area of these environments range from tens to thousands of square meters, equipped with industrial robot and other equipment. The environment has high levels of EMI. Lighting level of 150 lux is recommended (1500 lux for dedicated work).

Applications
Ultra-high-definition (UHD) video streaming for surveillance or production monitoring (quality control) applications, as well as for video collaboration for team, customer, and supplier meetings. Lightly compressed Video: ~ 1Gbps, delay < 5 ms, 1x10-8 PER, 99.9% reliability.

Fully connected factory—for real-time communications, application execution, and remote access.

Distance between LC APs ranges from 2~20 meters.

Traffic Conditions

Both uplink and downlink traffics are [JK1] using LC. High levels of OBSS interference between LC access points (APs) expected due to very high density deployment. Potential non-LC interference from surrounding environments such as artificial-light. Multiple LC modules are deployed on the robot/equipment and on the ceiling/walls to provide multiple light links for a robust connectivity in case a single line-of-sight (LOS) link is blocked.

Use Case

An industrial robot is powered on and ready for operation. Operating instructions are transmitted to the robot via LC. The robot is working (e.g., movement) according to the instructions and provides real-time feedback information and/or video monitoring data for quality control to control center also via LC. Upon command, the robot finishes the task and is ready for the next one.

Figure 1 Industrial Wireless Use Case

Usage Model 2: Wireless Access in Medical Environments

Pre-Conditions

IEC 60601-1-2 standard recommends the minimum separation distance between medical electrical (ME) equipment and RF wireless communications equipment (e.g., wireless local area network (WLAN)) be 30 cm to avoid performance degradation of the ME equipment. LC is deployed to ensure the performance of all ME equipment.

Environment

The size of an operating theater and MRI room ranges from 30~60 m2. Multiple LC-APs are deployed on the ceiling to provide specialized illumination. The central illuminance of the operating light: 160k and 40k lux. The size of a four beds ward is about 60 m2, light level: 300 lux on the bed and >100 lux between the beds and in the central area.

Applications

LC-WLAN is used to allow wireless data exchange in medical environments with ME equipment or system. Medical multimedia and diagnostic information can be transmitted to provide telemedicine services; ME equipment can also be wirelessly controlled via LC. Provide Intranet/ Internet access, audio or video call for doctors, nurses and patients using LC-based devices.

Traffic Conditions

No interference caused by RF radiation. Both uplink and downlink traffics are using LC. High Quality of Service (QoS) and high reliability are required. Potential non-LC interference from surrounding environments such as artificial-light.

Use Case

Doctors enter an operating room, turn on the LC enabled LED lights and ME equipment. Doctors can interact with the remote doctors and share information using LC. ME equipment connectivity is also supported by LC. Doctors finish the treatment, then turn off the lights and medical equipment.

Figure 2 Operating Theater Use Case [1]

A patient is monitored by ME equipment which communicate with the nurses/doctors in control room via LC.

Usage Model 3: Enterprise Network

Pre-Conditions
The density of users may be very high in the space such as enterprise environment leading to slow speed or even dropped or lost connections. LC is deployed to provide wireless connectivity escaping the limitation.

Environment
Recommended size of a meeting room for 30 seats ~ 50 m2. Mostly LOS with a few obstacles for example slow moving people. Dense stations (STAs) (20~40 STAs) in one meeting room with up to ~10 APs. Max distance between AP and STA ~ 5 m. The inter-LC AP distance is in the range of 1~3 m. Lighting level of 500 lux is recommended.

Figure 3 Meeting Room Use Case [1]

Applications
UHD Video conference up to 1Gbps, Virtual desktop, Intranet/Internet access or File exchange between two/multiple users in the same room.

Traffic Conditions
Both uplink and downlink traffics are using LC. High levels of OBSS Interference between LC access points (APs) expected due to very high density deployment. Interference with peer-to-peer networks within each meeting room. Potential non-LC interference from surrounding environments such as sunlight and artificial-light.

Use Case
UHD video teleconferencing starts in multiple meeting rooms simultaneously. People can see each other and demonstrate their desktop to each other via the LC network. Some people are walking in the meeting room.

Usage Model 4: Secure Home Network

Pre-Conditions
RF based WLAN signal can be received by surrounding devices belonging to legal users or hackers. This potential risk causes concerns among wireless users who are especially aware of their data security and privacy. LC is deployed to provide wireless connectivity with limited coverage and solve this problem.

E**nvironment**
A living room with an area of up to ~ 30 m2, installed with 5-30 ceiling lamps, a floor lamp and a table lamp.

Mostly LOS with a few obstacles for example furniture. Up to ~10 STAs in one room, the distance between AP and STA 0.5 ~ 3 m. The inter- LC AP distance is in the range of 0.5 ~ 2 m. Recommended illuminance levels for general lighting, recreation and reading are 50 lux, 200 lux and 500 lux, respectively.

Applications
Secure wireless Internet access (20 Mbps per user) 3D UHD lightly compressed video (3.6 Gbps)

Traffic Conditions
Both uplink and downlink traffic is using LC. High levels of OBSS Interference between LC access points (APs) expected due to very high density deployment. Interference with peer-to-peer networks within the same room. Potential non-LC interference from surrounding environments such as sunlight and artificial-light.

Use Case
Users perform a mixture of applications, including Internet access, online video chat, without worrying about wireless signal leaking into other places.

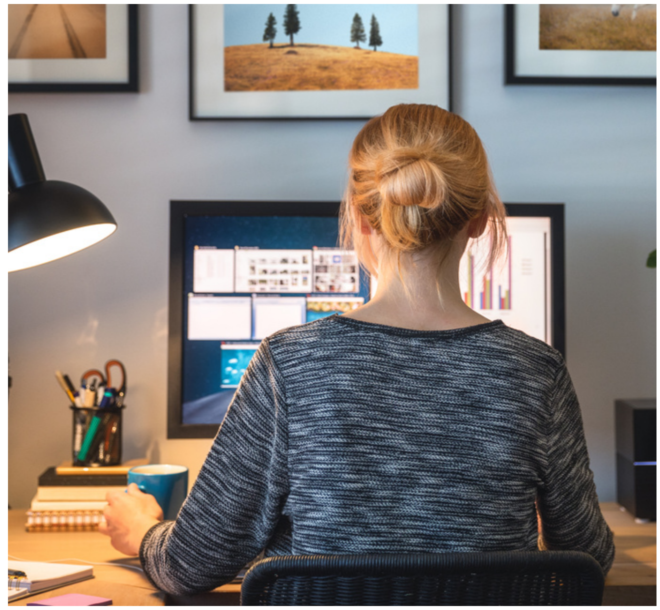

Figure 4 Home Internet Access Use Case

Key Considerations of the Usage Cases

UC#	Distance	Throughput	Latency	Applications & Characteristics
Industrial Wireless	<20m	10Mbps~1Gps	<1ms	-Production monitoring -Static, Low Mobility (1-2 m/s) -Infrastructure mode
Wireless access in medical environments	<3m	10Mbps~3Gps	<1ms	-Uncompressed UHD -Static, Low Mobility (1-2 m/s) -Infrastructure mode
Enterprise network	<5m	10Mbps~1Gps	<1ms	-Video broadcasting -Static, Low Mobility (1-2 m/s) -Infrastructure mode
Secure home network	<3m	10Mbps~5Gps	<1ms	-Internet, Video -Low Mobility, (1-2 m/s) -Infrastructure mode

Table 1 Key Considerations of the Usage Cases

802.11bb determined below usage models can be considered as secondary applications of light communications [2].

1. Backhaul
2. Vehicle to Vehicle Communication
3. Vehicle to Infrastructure and Infrastructure to Vehicle Communication
4. Underwater Communication
5. Gas Pipeline Communication

IEEE 802.15.13 Optical Wireless Communication Standard

IEEE STD 802.15.13 describes the use of optical wireless communication for wireless specialty networks. Some of the characteristics found in the standard are as follows [2]:

- Star topology supporting point-to-point, broadcast and multiple-input multiple-output (MIMO) operation
- EUI-48 MAC addresses
- Scheduled or polled medium access with random initial access
- Flexible medium access schedules allowing for the support of isochronous traffic
- Acknowledgment and retransmission protocol for transfer reliability

The IEEE Std 802.15.13 device architecture is defined in terms of layers. The standard includes a specification of the PHY and MAC sublayer and their exposed interfaces. Each layer is responsible for one part of the standard and offers its services to the next higher layer. Layers make use of service access points (SAPs) based on primitives, described in IEEE Std 802.15.4™-2020. Figure 5 depicts the architecture of a single device.

Each device has a device management entity (DME), responsible for managing the device and, in case that the device is a coordinator, the OWPAN. The DME invokes MAC layer management entity (MLME) functionality through the MLME service access point (MLME-SAP). The MLME-SAP defines a set of essential primitives for network operation. Further functionality is potentially provided by the MAC sublayer to the DME in an implementation specific manner.

The IEEE Std 802.15.13 MAC sublayer controls access to the medium for all types of transfers. It provides the MD-SAP and MLME-SAP to the higher layers. Its MD-SAP allows the next higher protocol layer to transmit MAC service data units (MSDUs) between peer IEEE Std 802.15.13 devices by supporting the MAC service defined by IEEE Std 802.1AC™. The higher layers are a network layer, which provides network configuration, manipulation, and message routing, and an application layer, which provides the intended function of the device. The definition of these higher layers is outside the scope of this standard. The PHY contains the optical wireless transceiver, which is responsible for turning a PHY service data unit (PSDU) into a PPDU for transmission. PSDUs are MPDUs from the MAC sublayer that are transferred through the PHY data service access point (PD-SAP) of the PHY. To yield the PPDU, a PSDU is supplemented with various fields, needed by each respective PHY for reception. Thereafter, the PPDU is output to one or more OFEs as an analog signal. Management functions of the PHY are invoked through the PHY management entity service access point (PLME-SAP).

The standard defines two physical layers (PHYs), Pulsed modulation PHY (PM-PHY) and High bandwidth PHY (HB-PHY).

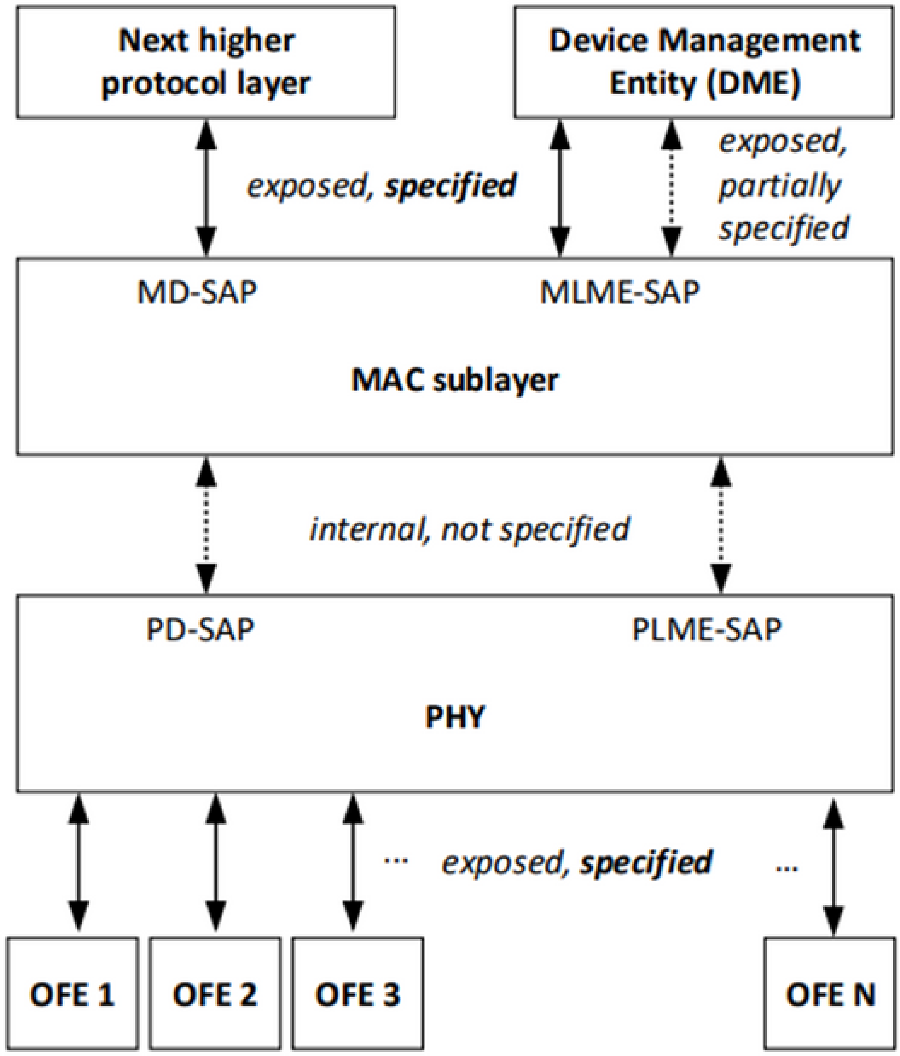

Figure 5 OWPAN Device Architecture [2]

Pulsed Modulation PHY

The PM-PHY is intended for moderate data rates between ~9 Mb/s and ~100 Mb/s, low power and low latency. It allows fast adaptation to the time-varying channel in mobile scenarios. The unique approach of the PM-PHY is to use a high clock rate and modulation with low spectral efficiency. This approach offers enhanced reach in applications where power efficiency is an issue, e.g., the Internet of Things (IoT).

Binary pulse-amplitude modulation (2-PAM) with 8B10B line coding, as defined in 10.3.5 is supported. It is combined with Reed-Solomon (RS) FEC. Moreover, the PM-PHY provides means to estimate the channel impulse response of multiple LED lights simultaneously. The PM-PHY supports MIMO transmissions via multiple OFEs.

High Bandwidth PHY

The HB-PHY is intended for low latency and very high data rates, between 23 Mb/s and 2.192 Gb/s. It allows fast adaptation to the time-varying channel in mobile scenarios. The unique approach of the HB-PHY is to combine a high bandwidth with a high spectral efficiency. For modulation of the LED, multiple bandwidths are used. DC-biased OFDM is used in combination with adaptive bit loading, applying quadrature amplitude modulation (QAM) with variable constellation sizes on each subcarrier or subcarrier group. Low-density parity-check codes (LDPC) with variable code rates and different block sizes are used for FEC. Moreover, the HB-PHY provides means to estimate the channel impulse response of multiple LED lights simultaneously. The HB-PHY supports MIMO transmissions via multiple OFEs.

IEEE 802.11bb Light Communications Amendment

The IEEE 802.11bb Task Group on Light Communications was tasked on introducing necessary changes to the base IEEE 802.11 Standards to enable communications in the light medium. The general scope for the Task Group was limited to:

- Uplink and downlink operations in 800 nm to 1,000 nm band,
- All modes of operation achieve minimum single-link throughput of 10 Mb/s as measured at the MAC data service access point (SAP),
- Interoperability among solid state light sources with different modulation bandwidths.

As of April 2023, the Task Group finalized its work and the draft amendment is on the list for approval in IEEE SA [3]. The amendment supports the PHY layers of 802.11n (Wi-Fi 4), 802.11ac (Wi-Fi 5), and 802.11ax (Wi-Fi 6) amendments. This is achieved by upconverting the complex baseband waveform associated of each to an LC IF signal, either directly or by up/down conversion. A DC bias is added to the LC IF signal which is then fed into an optical front end (OFE). The OFE converts the DC biased LC IF signal into an intensity modulated optical signal. Figure 6 both options are shown. In the second option it is possible to use the existing Wi-Fi chipsets. A DC bias is added to the LC IF signal before the signal is fed to the transmitting OFE because the current through a light emitting device can only be positive.

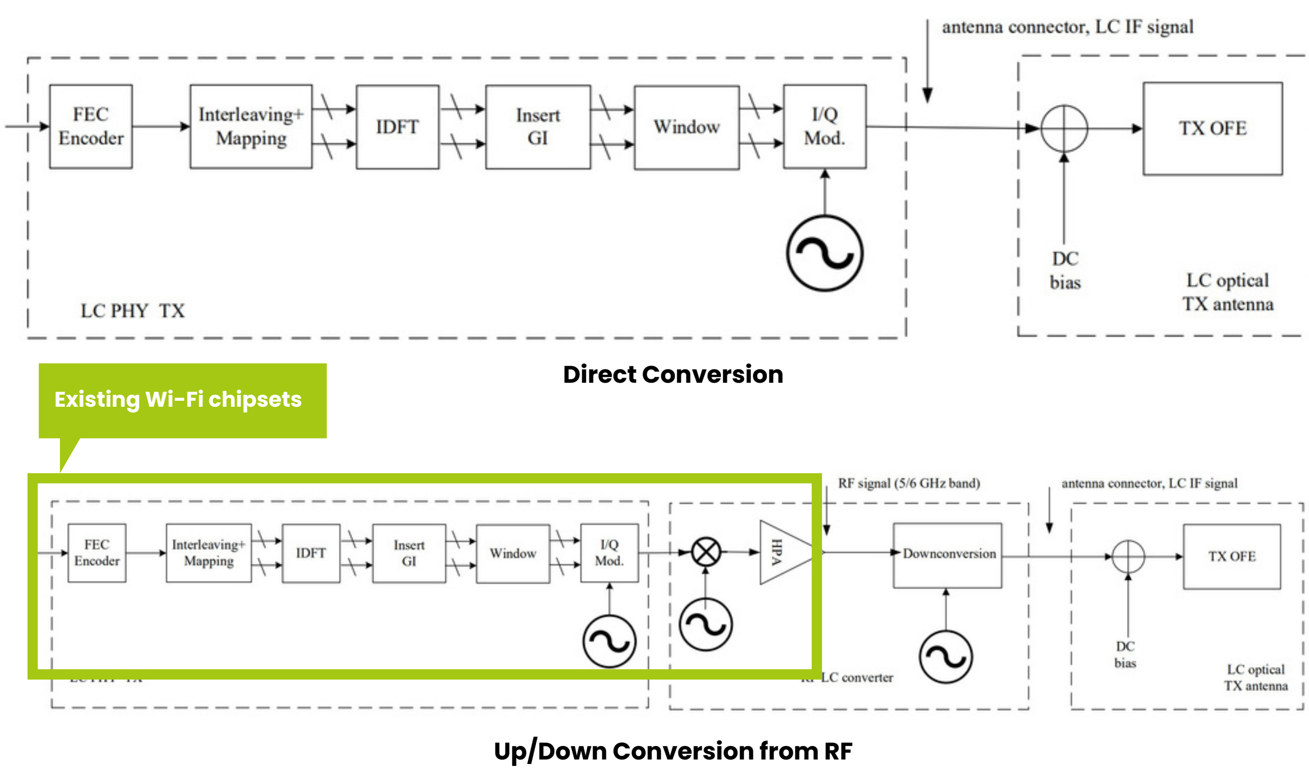

Figure 6 802.11bb Implementation Options [4]

802.11bb systems will support MIMO communication and spatial and wavelength multiplexing. Spatial multiplexing is supported when LC optical RX antennas and LC optical TX antennas are positioned such that light transmitted by an LC optical TX antenna incident on an LC optical RX antenna is at least partially isolated from the light transmitted by another LC optical TX antenna that is incident on another LC optical RX antenna. The isolation might be achieved by directing the light at the optical TX antenna or capturing light from a particular direction at the optical RX antenna. The isolation might also be achieved by spatially separating the LC optical TX antennas and/or LC optical RX antennas. Wavelength division multiplexing is supported when the wavelength of the light transmitted by one LC optical TX antenna is different from the wavelength of the light transmitted by another LC optical TX antenna and, correspondingly, one LC optical RX antenna is sensitive to the light of the first wavelength but not the second wavelength and another LC optical RX antenna is sensitive to the light of the second wavelength but not the first wavelength.

References

[1] Oliver Lus et al., LC Usage Model Document , Jul 2018 [online] Available: https://mentor.ieee.org/802.11/dcn/18/11-18-1109-05-00bb-lc-usage-model-document.pptx

[2] IEEE Approved Draft Standard for Multi-Gigabit per Second Optical Wireless Communications (OWC), with Ranges up to 200 meters, for both stationary and mobile devices

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About the Author

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Tuncer Baykas is currently senior technical staff at Ofinno. He received his Ph.D. degree in electrical engineering from the University of Ottawa. He joined the National Institute of Information and Communications Technology, Japan, in 2007.

During his tenure, he contributed to multiple standardization projects, including IEEE 802.15.3c, IEEE 802.11ad, and IEEE 1900.7. He served as the Chair for IEEE 802.19.1 coexistence in the TVWS Task Group. Between 2012 and 2014, he worked as a postdoctoral researcher at Tohoku University, where he contributed the development of the IEEE 802.15.4k Low Energy Critical Infrastructure Management Standard. Between 2016 and 2019 he represented NICT in the International Telecommunication Union Radiocommunication Sector, and he was drafting group Chair of the 1A-3 and 5C-3 groups on WRC-19 agenda item 1.15.

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