ELIoT

Enhance Lighting for the Internet of Things

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Open Reference Architecture and Software Library

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Abstract

The document introduces the ELIOT open reference architecture and shows its close relation to other standardized reference architectures. The open reference architecture for the future connected lighting infrastructure is aimed to facilitate integration of VLC into various IoT applications, as described and specified in the extended use cases section of this document covering the wide variety of LiFi deployments as addressed in ELIOT.

The defined architecture represents a common view on partitioning of end-to-end applications into functional building blocks, together with the identification of appropriate interfaces enabling, thus, the interworking of components made by different manufacturers. Architectural aspects of integration of LiFi into various kinds of networks, e.g. enterprise, industrial, or residential, but also 4G/5G mobile networks are addressed as well. The open reference architecture will be publicly shared at standardization meetings and conferences to foster the adoption of a common model for the development and implementation of LiFi interfaces.

The common model is accommodated by the LiFi reference software library, which has the objective to provide a toolbox for evaluation of new functions for the support of mobile IoT devices including means for optimization and verification of results. The software library consists of multiple @Matlab based functions, which can be used for applications like LiFi system performance analysis, network planning, modelling of LiFi channel impairments, and various aspects of testing.

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Executive summary

This document defines a generic open reference architecture of PHY layer and DL layer functions of a LiFi communication interface together with system management functions for the interface as well as the adaptation layer to various network layer protocols in the data path. Optional extensions to the open reference architecture are proposed for representation of advanced features like AP function, fronthaul, and various kinds of MIMO deployments. The defined reference architecture is closely aligned with the reference models standardized in IEEE 802.11, IEEE 802.15.13, and ITU-T G.9991, and can be easily deployed in various IEEE 802 based access networks as defined in IEEE 802.1CF, as well as integrated with 5G systems following the 3GPP specification TS 23.501.

The open reference architecture is derived from architectural considerations of ELIOT use cases and adopts the generic layered architectural concepts of open systems interconnection as specified in ISO/IEC 7498-1 and follows industrial practices for defining open interfaces.

The related reference model software library has the objective to provide a toolbox for evaluation of new functions for the support of mobile IoT devices including means for optimization and verification of results. The software library consists of multiple @Matlab based functions which can be used for applications like LiFi system performance analysis, network planning, modelling of LiFi channel impairments, and various aspects of testing.

The document facilitates standardized interfaces for LiFi communication interfaces to allow for easier deployment and adoption of the technology to a broad variety of use cases, to enable synergies in the design and development of circuitry and driver software, and to foster the market availability of interoperable chip solutions.

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Index of terms

AMF	Authentication and Mobility management Function
AP	Access Point
ARC	Access Router Control
BW	BandWidth
CPU	Central Processing Unit
CSMA	Carrier Sense Multiple Access
DL	Data Link
DLL	Data Link Layer
DLSAP	DL Layer Service Access Point
DMT	Discrete MultiTone
DSL	Digital Subscriber Line
ETH	Ethernet
FOV	Field Of View
FTTH	Fiber To The Home
IP	Internet Protocol
LCI	Light Communication Interface
LC	Light Communication
LiFi	Light Fidelity
LLC	Logical Link Control
LLSAP	LLC Layer Service Access Point
LMSAP	LLC layer Management Service Access Point
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MLSAP	MAC Layer Service Access Point
MMSAP	MAC layer Management Service Access Point
MU-MIMO	Multi User MIMO
N3IWF	Non-3GPP InterWorking Function
NA	Node of Attachment
NMS	Network Management System
OFDM	Orthogonal Frequency Division Multiplex
OFE	Optical Front End
OSI	Open System Interconnection
OWC	Optical Wireless Communication
PHY	Physical
PLC	Power Line Communications
PLSAP	PHY Layer Service Access Point
PMSAP	PHY layer Management Service Access Point
POF	Plastic Optical Fiber
QoS	Quality of Service
RFE	Radio Front End
RF	Radio Frequency
SAP	Service Access Point
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SMF	Session Management Function
SMSAP	System Management Service Access Point
STA	Station

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SU-MIMO	Single User MIMO
TEC	Terminal Control
UE	User Equipment
UPF	User Plane Function
USB	Universal Serial Bus
Wi-Fi	Wireless Fidelity

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Content

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1. Introduction

Light communication or LiFi, as it is often called, is an emerging technology that provides unique features through the usage of the enormous amount of spectrum of light. It delivers clear benefits for the realization of reliable wireless high-speed communications and has broad applicability to many different use cases through its usage of unlicensed spectrum and wide scalability from low power small bandwidth to extreme mobile broadband and ultra-reliable low latency communications.

As there is not the single extreme high-volume compelling use case ('killer application') but a variety of beneficial deployments of moderate market volume each, functional similarities among the use cases must be identified to allow for the definition of common building blocks for the design of the light communication interface circuitry as prerequisite for chip designs that are able to serve a wide variety of use cases and finally reach the economy of scale necessary for successful market introduction. As applications are evolving over time and new deployments may be identified while gaining application experience, there is need for flexibility and extensibility of the architectural approaches to cope with future demand. A common open reference architecture for the LiFi interface is seen as a beneficial tool to foster the broad market introduction of light communication technologies.

This document aims to fill the gap and to provide an initial proposal for an open reference architecture, which will be revised and refined during the ELIOT project based on the experiences gained in the development tasks of the various demonstration cases.

Following the introduction of the basics of the ELIoT Flexible System Concept in chapter 3, a compact presentation of all the guiding use cases in ELIoT and their functional requirements for the LiFi interface are provided in chapter 4, and the LiFi open reference architecture is derived and developed in chapter 5 adopting common principles of open system interconnection design. Internal as well as open external interfaces of the LiFi interface are introduced, and various optional extensions for specific functional requirements are proposed. Chapter 6 shows the alignment of the proposed open reference architecture with existing light communication interface designs and developments, and chapter 7 addresses the deployment of the specified LiFi interface within the most widely deployed network architectures. Chapter 8 contains the introduction of the reference model software library that delivers software components to allow for efficient evaluation of new ideas to enhance the performance of the main standardized LiFi interfaces. Potential directions for amendments to this document are provided in the concluding chapter 9.

2. Scope and purpose of this document

2.1. Scope

This document defines a generic open reference architecture of PHY layer and DL layer functions of a LiFi communication interface together with system management functions for the interface as well as the adaptation layer to various network layer protocols in the data path. Optional extensions to the

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open reference architecture are proposed for representation of advanced features like fronthaul, MIMO, or positioning.

2.2. Purpose

This document facilitates standardized interfaces for LiFi communication to allow for easier deployment and adoption of the technology to a broad variety of use cases, to enable synergies in the design and development of circuitry and driver software, and to foster the market availability of interoperable chip solutions.

3. Flexible System Concept

As LiFi serves many diverse niche applications, fostering a single mass market is only possible to a limited extent. However, to achieve low prices, it is crucial that large volumes of hardware, i.e., chipsets and electronic circuits, are fabricated. Considering the different requirements, it seems unlikely that a monolithic solution serves all use cases optimally. This section presents a flexible concept for functional components, which can be used to assemble solutions for the various use cases, while allowing for commonalities for increased reusability of hardware and software.

3.1. Components of system concept

The following aspects are covered through the system concept:

- **Network integration of LiFi** as a layer 2 local area network (LAN), equivalent to a classical Ethernet connection, is needed explicitly for some use cases and provides good versatility by supporting various protocols like the Internet Protocol (IP) or industrial automation protocols like ProfiNet. The LiFi system will therefore integrate as a LAN, conform to the IEEE 802 family of standards. As a result, integration with 5G networks can be realized based on existing functions for non-3GPP access as defined in 3GPP TS 24.502.
- **Common physical layer (PHY) convergence formats** are important for harmonization and constitute the key commonality of solutions together with common MAC frame formats. Compatibility at the PHY is possible by selecting a common mandatory transmission mode, used for network access and spectrum coordination. In a packet based PHY, control information in the mandatory mode can precede all frames and indicate e.g. usage of a more optimized mode for the rest of the frame.
- The **PHY** can make use of direct current (DC)-biased bit-loaded orthogonal frequency-division multiplexing (OFDM) with powerful forward error correction to deliver high data rates even under more challenging conditions [5]. The achievable system bandwidth depends on multiple factors and the technologies of OFEs are continuously enhanced to provide more bandwidth. The ability to scale the number of subcarriers for arbitrary bandwidth and to adapt transmissions through bit- and power-loading is perfect to exploit the full capacity of LiFi. First LiFi systems already use this type of PHY with great results leveraging chipsets aimed for home networking.
- The **MAC** frames for all solutions are kept compatible as well. While solutions are not required to support every frame, all solutions should support a basic set. Based on that core set, capabilities can be signaled and usage of advanced functionality and frames negotiated.

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- **Distributed MIMO** is optional and supports multiplexing or diversity based on subcarrier-wise channel estimation, feedback of channel state information, precoding, and equalization for a scalable number of OFEs. Accessible interfaces allow the PHY to be split into centralized and distributed functions over a so called fronthaul, following the functional split paradigm from cellular networks. Centralized scheduling algorithms on the medium access control layer (MAC) allow the realization of distributed MIMO at locations where installing the fronthaul is possible. Through distributed MIMO, the impact of frequent handovers due to the small cell size of LiFi can be overcome and a consistent QoS and reliability can be provided for high mobility and high user densities.
- **Support for battery constrained devices** includes a low complexity PHY with low power consumption. For example, on-off keying with frequency-domain equalizing can be used instead of the DC-biased OFDM. For increased synergies in the hardware, the same error coding, scrambling, block length, and cyclic prefix can be used but the Inverse Fast Fourier transform (IFFT) shifts from the transmitter to the receiver as proposed in [6]. The usage of such low complexity PHY as common mode is a natural choice. On the receiver side, devices can leverage energy harvesting receiver techniques based on photovoltaics to increase battery life significantly.
- For **integrated positioning**, the PHY includes optional means to perform sub-sample accurate timing measurements through phase estimation in the frequency domain. Based on that feature, the MAC is able to perform ranging, which allows precise time-of-flight measurements between the OFEs and terminals. By means of a corresponding anchor point, a multilateration algorithm can calculate the position of the terminal.
- The **channel access mechanism** should support reservation-based access for traffic flows with guaranteed throughput and bounded latency, to meet the demanding requirements of future IoT traffic. Power saving through scheduled sleep periods supports longer live-times in battery-powered operation. For static P2P links, the channel access can be preconfigured as transparent pass-through, avoiding excessive queueing for multiple access in favor of ultra-low latency and full duplex communication.
- The **backhaul** connects the APs to an access network with a common interface to higher layer services. This backhaul network may be realized over different media, each having its own capacity and latency characteristics. While power-line communication (PLC) allows for retrofitting, the backhaul may also be realized using, e.g., an Ethernet network. A unified interface for the backhaul network allows versatile integration.
- For the **handover between LiFi and Wi-Fi**, APs and devices could provide interfaces for the IEEE 1905.1 standard. The interfaces allow a router to determine the best route of layer 2 packets to the mobile terminal and forward them accordingly. In home environments, the functionality is seamlessly integrated into the home router.

3.2. Extended functionality

Extended functionality can be made available to each solution through software modules. Software functions are only included in solutions, which require them. Functions comprise link monitoring, remote configuration based on standardized protocols, as well as QoS management and service metering. Besides standard processors, the chipset integrates hardware acceleration blocks for the

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support of some of the functionality. Open interfaces of the hardware allow the exploration and implementation of new functions through software.

4. Use cases and functional requirements

4.1. Office

4.1.1. Functional characterization

In a typical office building an enterprise network solution provides internet connectivity via Wi-Fi and LiFi. RF spectrum can be relieved and new applications can be allowed (e.g., wireless screen sharing) by deploying LiFi as a capacity booster next to Wi-Fi. State of the art secure individual authentication and encryption over the air are required.

The LiFi integrated luminaires are used to offload traffic from Wi-Fi (and potentially 5G) towards the unregulated light spectrum offering improved bandwidth and dependable quality of service. As LiFi is not trespassing building walls, interference is limited to the single room and network intrusion is hampered.

The typical locations to provide LiFi connectivity are offices and meeting rooms where most terminal connections are to stationary locations (e.g., on the table) and end devices are essentially not moving. Still, it is required to support connectivity for moving end-user devices. A 'multi-cell' infrastructure will be realized for seamless connectivity across the office area to serve moving LiFi devices. A coordinator manages multi access point connections.

Office spaces have potentially a high density of devices to connect. MIMO solutions will be used in ELIOT mostly for improved ruggedness of the connection. The wired broadband backhauling will be realized by Ethernet preferably using an existing infrastructure. The fronthaul deployment towards the optical frond ends through POF will be assessed as alternative to the wired connection used so far.

At least 50 Mbit/s uplink and downlink speed are required for each user at 99.9% of time to serve any modern office application. Typical business traffic includes Internet browsing, remote desktop sharing and server usage, file download, teleconferencing, etc.

4.1.2. System architecture overview

The general architecture for the office use case is depicted below where AP stands for access point and OFE for optical front end.

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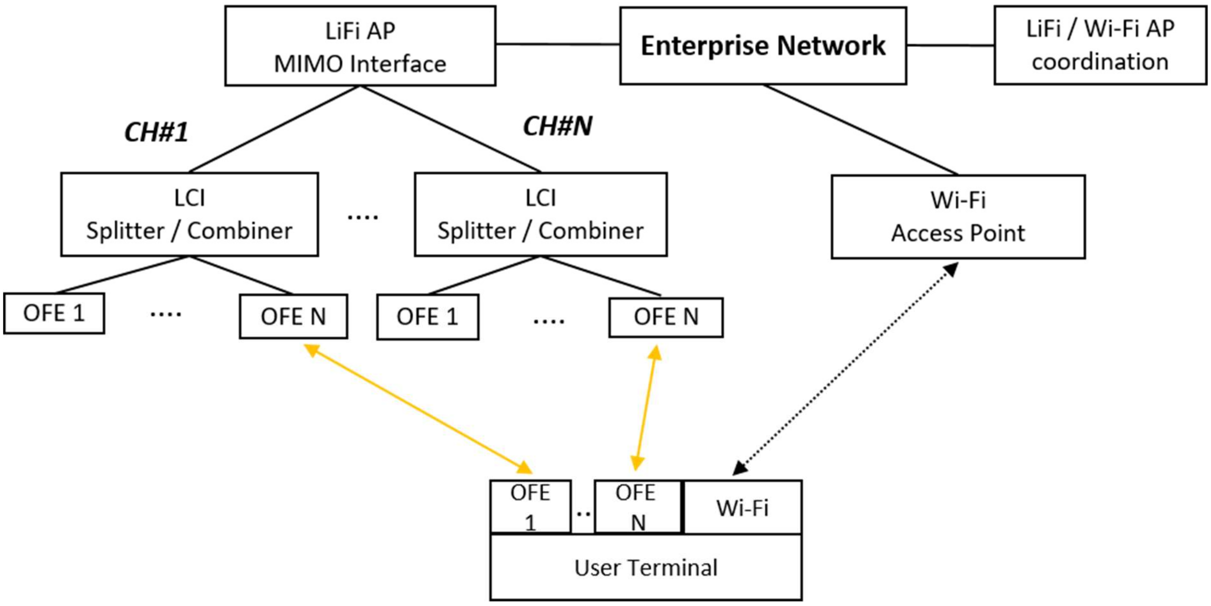

Figure 1: Office – system architecture overview

4.1.3. LiFi functional requirements

Seamless large area coverage through multiple LiFi APs must be provided together with low power consumption and low-cost terminal interfaces. Management and service of the LiFi network components needs to be fully integrated with corporate IT.

Support of various moving terminal scenarios is required:

Terminal moving within the coverage area of a single AP

In this scenario, a single LiFi-AP comprising multiple OFEs, provides LiFi access within a single area (e.g. a single room). It is thereby assumed that no other LiFi-AP is visible within that area, meaning that no interference occurs through other APs.

To establish a robust LiFi connection, the LiFi-AP may activate multiple OFEs for each terminal. It enables to keep the connection alive when line-of-sight blocking towards a single OFE occurs. Moreover, when the terminal moves (changing its location in the area or changes its angular orientation towards the OFEs), the connection can also be kept alive.

The LiFi-AP and terminal may further optimize the link performance by taking advantage of the light traveling over different paths.

The LiFi-AP can trade-off between robustness and power consumption. For maximum robustness, the AP may activate all its OFEs for a terminal. For minimum power consumption, the AP may activate a single OFE for a terminal.

If a terminal moves within the coverage area of the LiFi-AP, the latter can adapt the connection to the terminal by changing the selection of active OFEs for this terminal and by adapting the physical layer parameters (e.g. bit loading) for optimal link quality.

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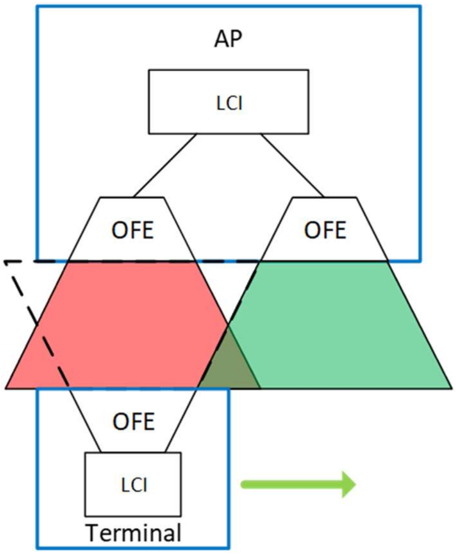

Figure 2: Terminal moving within LiFi AP coverage area

Terminal moving between APs with isolated coverage areas

In this scenario, multiple areas are served by LiFi-APs, whereby these areas are optically separated. This is typically the case for the situation of multiple (small) rooms in a building. Each area is thereby covered by a single LiFi-AP and no interference occurs between these APs. For a moving terminal within one of these areas, the previous scenario applies. If a user moves its terminal from one area to another, he/she typically enters an intermediate area (e.g. corridor) where LiFi has no coverage, resulting the terminal to lose its LiFi connection. As soon as the terminal occurs in an area with LiFi coverage, it can re-connect via its LiFi interface. Such re-connection should be fast.

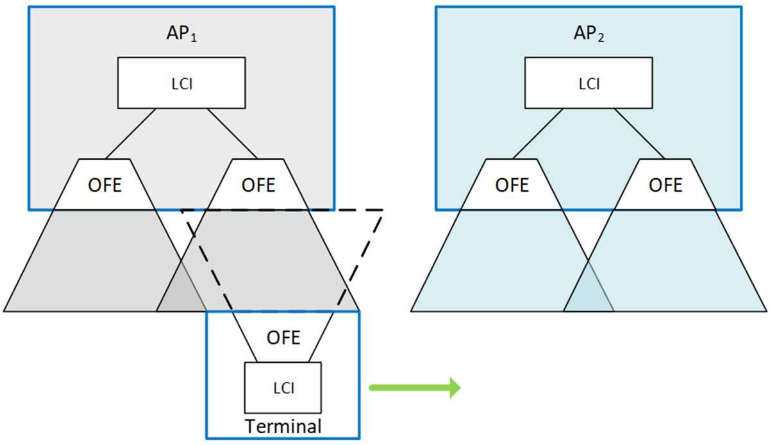

Figure 3: Terminal moving between LiFi APs with isolated coverage areas

Terminal moving between APs with overlapping coverage areas

In this scenario, a (large) area (e.g. open office) is served by multiple LiFi-APs with each AP covering part of the total area. The APs are optically not isolated as in the previous scenario. Instead, they intentionally have overlapping coverage areas to prevent dead zones. A terminal may therefore reside in the coverage area of multiple APs. It means that situations of unwanted interference can occur, which can be solved by coordinating the APs.

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For a terminal moving from one AP to a next AP, this scenario has similarity with Wi-Fi, meaning that a terminal can initiate handover from one AP to a next overlapping AP. This could be a “break before make” handover, whereby the LiFi link is briefly lost, but most preferably a “make before break” handover is supported in order to keep breaks of the LiFi link short.

LiFi differs from Wi-Fi regarding the size of overlapping coverage and the line-of-sight behaviour of LiFi.

Typically, the overlapping coverage area of LiFi is much smaller than for Wi-Fi at 2.4 or 5GHz, which puts an extra requirement on the speed of the handover process. A terminal may therefore preferably anticipate a handover by pre-registering to a neighbouring AP and pre-establishing security keys via the current active connection and the backhaul.

The line-of-sight behaviour of LiFi requires extra attention for the interference handling. A terminal has typically only a field-of-view (FOV) towards one or multiple APs, but not to any other terminal. An AP has typically only a FOV towards one or multiple terminals, but not to any other AP. It means that the carrier sensing of CSMA cannot be applied to prevent APs or terminals accessing the LiFi medium at the same time. Hence, access to the LiFi medium requires a more coordinated approach compared to Wi-Fi. For LiFi, it is therefore preferred that an AP controls the access of the terminals to the LiFi medium for uplink (terminal to AP) communication and that APs are coordinated to control their access to the medium.

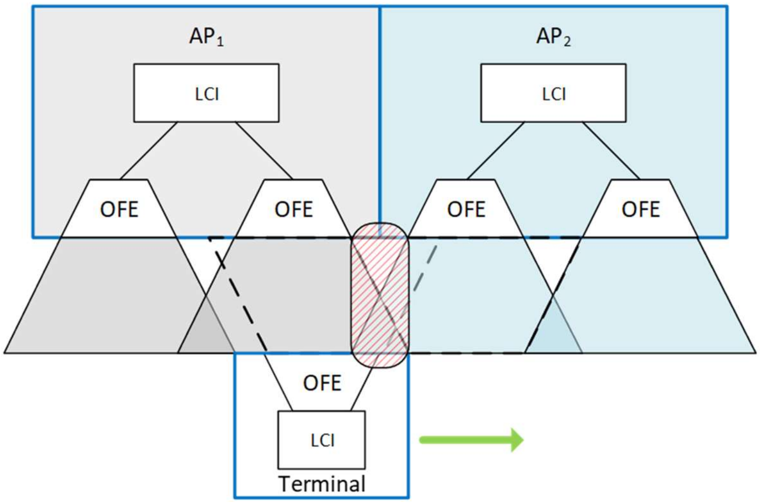

Figure 4: Terminal moving between LiFi APs with overlapping coverage areas

Terminal moving in/out of LiFi area within a Wi-Fi area

In this scenario, a small area (e.g. a single room) is served by a LiFi AP and a larger area (e.g. multiple rooms) by a Wi-Fi AP. For a terminal that moves in/out of the LiFi area, vertical handover between LiFi and Wi-Fi should take place. For a terminal that moves into a LiFi area, it enables to off-load traffic from Wi-Fi and to provide an increased QoS. For a terminal that moves out of a LiFi area, it enables to restore or keep the connection to the network through Wi-Fi. Figure 5: Terminal moving out of LiFi coverage area, remaining in Wi-Fi coverage area (different APs) illustrates this scenario for two physically separated APs and Figure 6 illustrates this scenario with a multi-protocol AP. Referring to

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IEEE802.11, this corresponds to fast BSS transition and fast session transfer, respectively. Note another way to realize the integration of LiFi and Wi-Fi is, by using the IEEE 1905.1 protocol and maintain layer 2 connectivity. This allows using two wireless techniques in parallel.

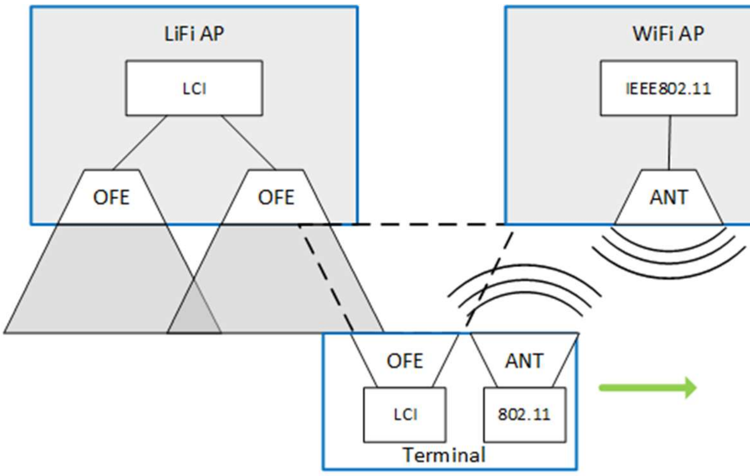

Figure 5: Terminal moving out of LiFi coverage area, remaining in Wi-Fi coverage area (different APs)

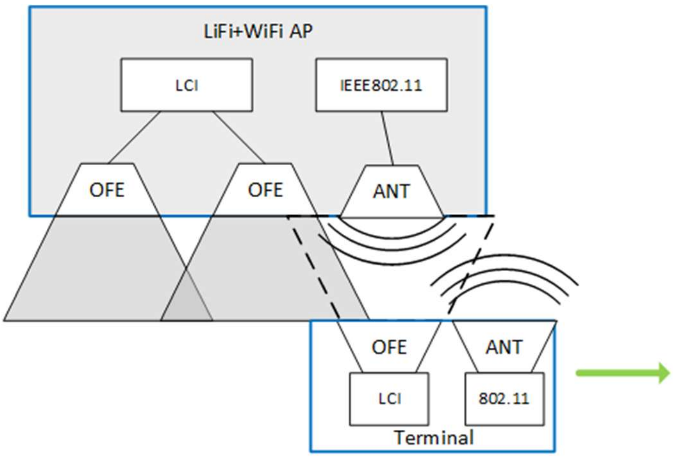

Figure 6: Terminal moving out of LiFi coverage area, remains in Wi-Fi coverage area (single AP)

4.2. Consumer home

4.2.1. Functional characterization

The consumer home use case envisions a seamless synergy between the well-established Wi-Fi usage by consumers and new LiFi hotspots for specific needs. These hotspots are spread across the house on places with a need for a stable high throughput connection such as the living room area, home office space or the backyard garden. They enable to offload traffic from Wi-Fi to LiFi in particular places of need but still have the freedom to move around independent of carrier technology.

Whereas Wi-Fi has the mesh functionality to form its own backbone connectivity between access points, LiFi has its own need for a separate infrastructure to connect the different access points to a central controller. For the consumer case the central controller should be the one appliance which is able to handle Wi-Fi, LiFi as well as acts as the home gateway router to your internet service provider.

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The luminaires have to be small, cheap as well as easy to install, replace and maintain. The infrared beams from the ceiling unit should cover an area of at least 2x2 m² in which the customer can deploy the terminal and still have a degree of freedom for proper placement of the transceiver. In case of nomadic or mobile user devices a single hotspot should be able to concurrently support several connections for the multiple users in a household.

LiFi enables typical residential traffic such as home networking, Internet browsing on desktop, tablets, smartphones etcetera but also novel applications such as virtual reality entertainment, very high-definition television, and live game streaming services.

4.2.2. System architecture overview

Figure 7 shows an architecture overview of the consumer use case. The internet service provider is connected to the home gateway/router which has the functionality to handle the Wi-Fi as well as the LiFi connectivity.

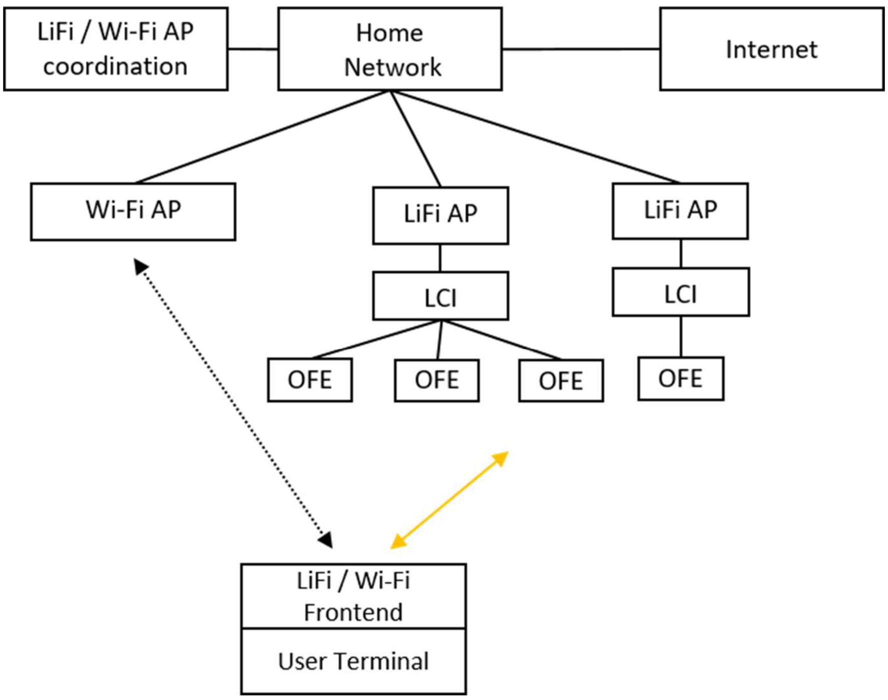

Figure 7: System architecture overview of consumer home use case

4.2.3. LiFi functional requirements

To transport the data traffic from the central home gateway through the house to the LiFi hotspots some sort of infrastructure is needed. Hence, the two main options considered are:

Power-line Communication (PLC)

Reuse the existing copper cabling is possible by applying PLC technology from the home gateway to each luminaire, see Figure 8: Connection of the home gateway to LiFi hotspots using power line communications. This would enable easy installation for the consumer where the data is modulated centrally on the mains group and can be converted back to the LiFi AP anywhere in the house. PLC conversion would be done once centrally and at each LiFi hotspot attached to the mains group. The limitation with this approach is that backhaul capacity is shared for all luminaires.

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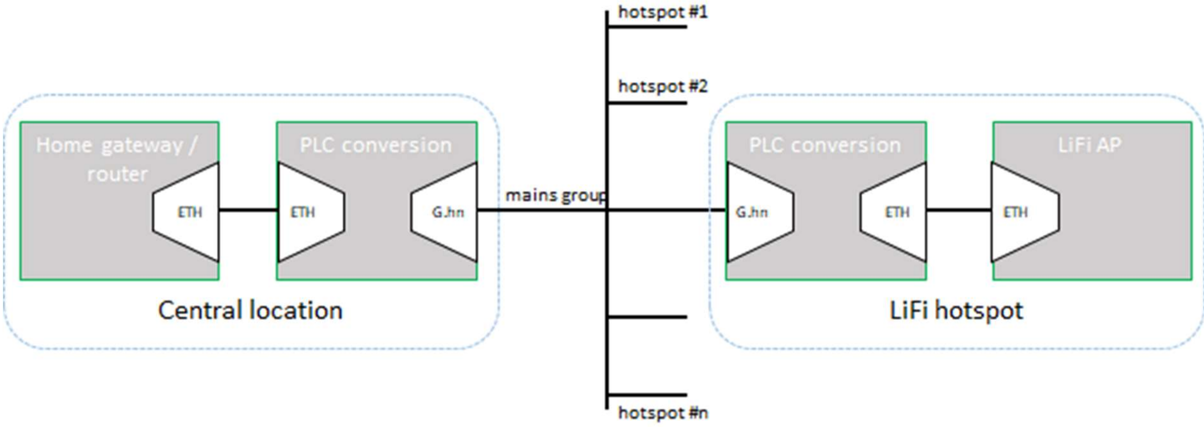

Figure 8: Connection of the home gateway to LiFi hotspots using power line communications

Plastic optical fiber (POF)

Consumers or skilled workers should be able to easily install new POF cabling through the duct leading to the central location where the home gateway is situated, see Figure 9: Connection of the home gateway to LiFi hotspots using plastic optical fiber. The splitting and combining of fibers should also take place here so it can be connected to the home gateway. In this situation each LiFi hotspot would get its own cabling and POF conversion from the AP to the home gateway. Recent tests indicated that the POF link can cover Gbit/s data rates, i.e. the limitation is always the wireless link, not the backhaul what is an advantage over powerline. Same as for powerline, there might be an intention to share the POF infrastructure which is possible using wavelength division multiplexing (WDM) but leads to higher complexity and cost.

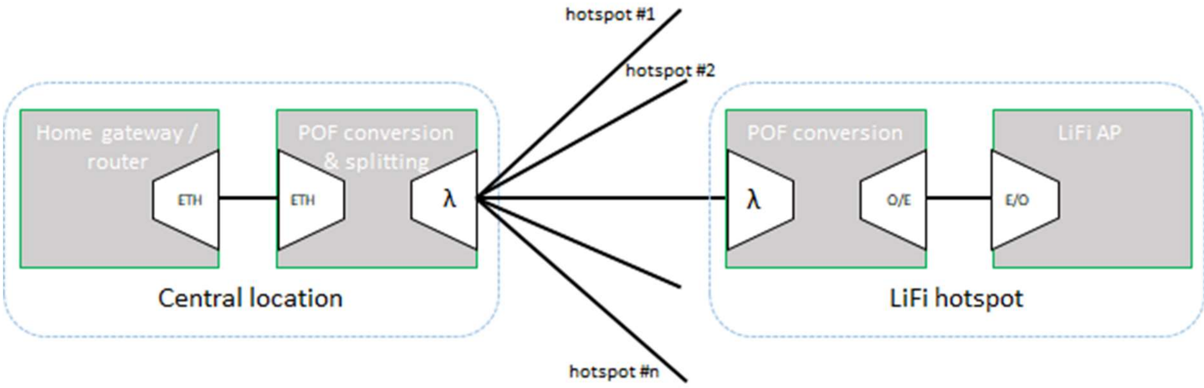

Figure 9: Connection of the home gateway to LiFi hotspots using plastic optical fiber

When both the Wi-Fi coverage and the LiFi hotspots are in place one needs to be able to switch the IP forwarding traffic with aggregation/vertical handover between the two techniques. This is similar as explained in the previous use case. From the end user perspective, the initial onboarding procedure is simple and almost effortless but with strong security. Afterwards, the handover decision-making and procedure is an automatic process which is centrally controlled so it does not require the end user to pay attention to it. The user terminal should be a low-power, low-cost device with standard interface such as USB or ETH.

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4.3. Fixed Wireless Access

4.3.1. Functional characterization

The Fixed Wireless Access (FWA) use case complements the Consumer Home use case, providing the interconnection between the Home Gateway Router and the Internet (Figure 10)

FWA using Optical Wireless Communication (OWC) links is used to provide wireless data connectivity up to at least 200 meters between a service provider network and one or more dwelling units of customers, in order to replace more cost intensive cable based digital subscriber lines.

Such OWC systems need to have line of sight (LoS) conditions between the LiFi Subscriber Line Access Multiplexer (LSLAM) at the network side and LiFi Modem at the customer site, establishing the data connection, similar to respective radio or THz links.

On the one hand, optical based wireless connection may be in competition to millimeter- or THz-wave based wireless access technologies, but on the other hand it also can be a good complimentary technology with respect to harsh weather conditions. If the performance of mm-wave systems decreases, then the performance of OWC-systems increases, and vice versa, at distinct weather conditions. Hence, both OWC- and mm-wave hybrid systems together offer a better overall connectivity performance. Therefore, OWC outdoor links are good candidates for hybrid FWA systems, complementing e.g. mm- or THz-wave systems.

OWC links have to perform broadband > 1 Gbit/s signals and reliable connectivity to the customers. An automated link establishment to enable zero touch provisioning and using unlicensed light spectrum reduces time and costs for setting-up the customer connectivity services. However, it also has to smoothly fit into the overall landscape of a town, not disturbing the aesthetic view of city planning authorities. Therefore, the OWC devices have to be small, well designed with low power consumption, and ease of implementation.

4.3.2. System architecture overview

Figure 10 shows the architecture of an FWA system, depicting the network side Wireless Distribution Network (WDN) of a Communication Service Provider for Internet connectivity deploying multiple Distribution Nodes (DN) , mounted e.g. at a light pole. It offers the opportunity to get power as well as data connectivity in city areas via existing duct systems, reducing the costs for providing an OWC based provider network. A DN contains multiple LiFi units which are connected via point-to-point or point-to-multipoint links to different Customer Nodes (CN) of consumers, providing broadband Internet connectivity services with > 1Gbit/s link capacities. For higher reliability under severe weather conditions, LiFi links could be combinded with an additional mmWave link.

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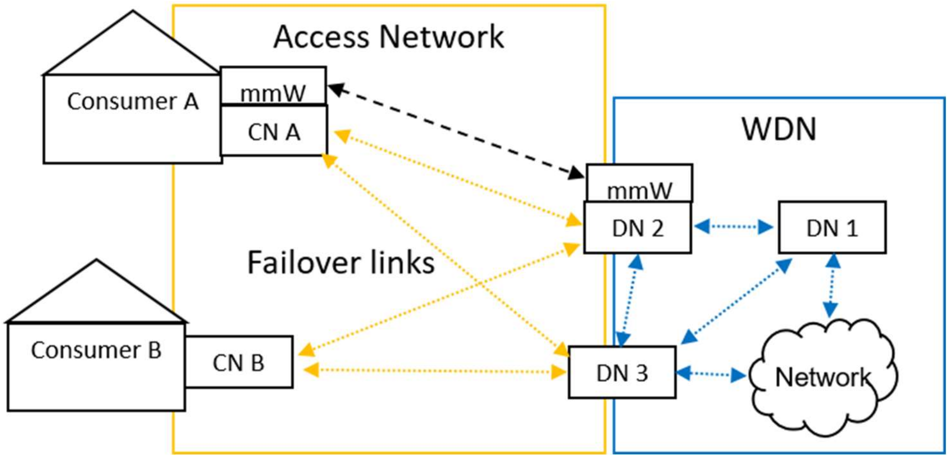

Figure 10: System architecture of FWA use case

The provision of typical broadband access services like Internet Protocol Television (IPTV), high speed Internet connectivity, and voice services may become more important by an increased use of teleconferencing and homeworking activities enabled also due to the Corona virus. Thus Gbit/s connectivity services using OWC are good candidates for FWA systems if they offer cost efficient higher link capacities or can complement competitive systems.

However, the classification and prioritization with at least 4 service classes may by useful for future LiFi systems, supporting sensitive real time services like teleconferencing, voice, and gaming.

Since LoS is essential for focused light beams of the FWA set-up, especially at longer distances beam steering systems may be relevant for future OWC systems.

A dual homing connectivity via e.g. two OWC systems from different light poles may also increase the bandwidth and reliability of future LiFi Digital Subscriber Lines, also supporting protection switching mechanisms if one connection fails.

Furthermore, a remote management including configuration, fault monitoring, and alarming are necessary functionalities to increase the availability of the OWC links, and in case of a failure of the time to service.

Finally, encryption functionalities have to be included to provide secure transmissions of sensitive customer data.

4.3.3. LiFi FWA functional requirements

The LiFi functional requirements are summarized for the FWA via OWC links.

- Transparent layer-2 connection
- Point-to-(multi)point connectivity
- Data rate of 1-2 Gbits/s per link
- Tx-Rx distances of 200 meters or longer
- Traffic classification and prioritization with 4 service classes or more
- Automated link establishment to enable zero touch provisioning
- Remote management including monitoring, configuration, alarming

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- Link protection mechanism in order to meet the requirement similar to DSL/FTTH
- Link encryption on the wireless link
- Low power consumption
- Small and smoothly designed OWC devices fitting into the city view

4.4. Positioning of Intelligent Transport Systems

4.4.1. Functional characterization

Production resources can be located on-demand, which enables new applications. Its position can be displayed on a factory map. This makes it possible to find a tool, a container with raw material or (semi-) finished products needed in a few seconds. Technically, this information could also be provided by an enterprise resource planning (ERP) system, but there would be no guarantee that the information provided represents the actual state in real time, as order confirmation is done manually. Moreover, faulty order confirmations can be reduced when the positioning system is used to support the process in such a way that confirmations are only possible, when the element of interest is present.

Furthermore, confirmation could also be done automatically, when the element is located by the positioning system, which reports the position to a manufacturing execution system (MES). This approach can significantly support the work of production planners that schedule production machines and resources because the list of resources that can be used is always up to date. This means that the production planner does not have to wait until the maintenance department has manually confirmed in the system that a maintained tool is ready for pick up. Instead, the tool can automatically be marked as “ready for production” as soon as it is detected on a “ready for production”-stockyard.

In another scenario, without such “ready for production”-stockyards, the technical staff from the maintenance department confirms manually that the tool is ready for production. Then, an ITS gets the actual tool position and can transport it directly to a machine where it is needed or into a tool warehouse.

Real-time positioning can also support technical maintenance staff or production managers. For example, tablets can support them by using the position information to display position-based information such as dashboards with machine data of the nearest machine(s).

The positioning scenarios described above can be summarized as follows:

1. positioning of transport systems,
2. positioning of mobile devices and
3. positioning of production resources.

The scenarios are similar and technically identical, but their requirements differ. Production resources are moved rarely. In contrast to this, mobile devices, such as tablets and smart glasses are moved more often, although for safety reasons, are only used when the user is stationary (at least, not walking at pedestrian speed). Even more so, transport systems are permanently moving.

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4.4.2. System architecture overview

Figure 11 shows the basic architecture of a LiFi based positioning system. Multiple LiFi APs are mounted at the ceiling and illuminate an area. Between the ceiling APs and the mobile terminal, MAC protocols routines for positioning exchange PHY frames with pilot signals. APs and terminals acquirer timestamps with high accuracy of transmission and reception. A fine timing information is extracted using a pilot signal-based phase estimation of the PHY and combined with the regular timing information. The infrastructure can be realized as multiple autonomous APs or as D-MIMO with ceiling OFEs as distributed units as part of a single AP [1]. In both approaches, an infrastructure network connects the LiFi OFEs. Ranging and multilateration algorithms determine the position of the terminal, which can be done anywhere inside the network.

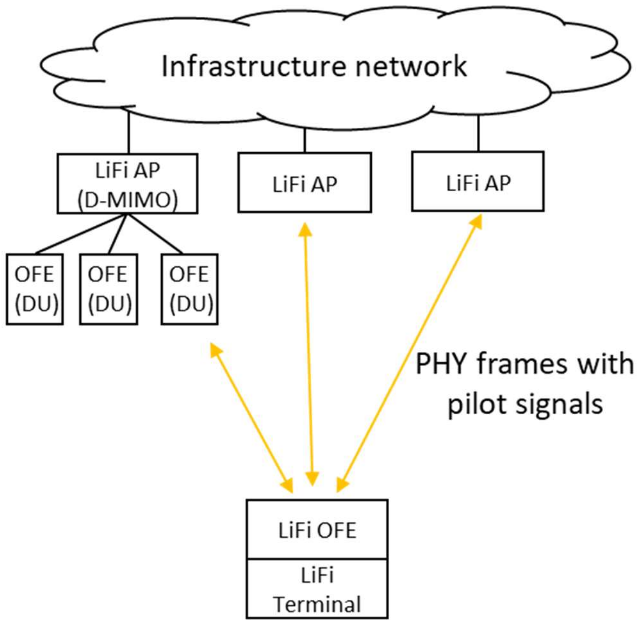

Figure 11: LiFi-based positioning infrastructure.

4.4.3. LiFi Positioning Functional Requirements

The functional requirements for positioning can be summarized as follows:

- Overlapping FOV of multiple ceiling APs to allow the 3D calculation from the ranging information
- Parallel connection of the mobile terminal to at least 3 ceiling APs
- Access to timing, channel, and similar signal information for each AP and or OFE in case of D-MIMO
- Round-trip-time estimation between ceiling AP and mobile terminal to avoid synchronization

4.5. Industrial Communications

In modern factories, production machines are connected with the factory network, because communication is the fundamental requirement for smart manufacturing. Most of them are equipped with a network interface and are directly connected to the network, while older machines

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need a retrofit for participation. Machines, retrofit devices, and mobile devices, such as tablets, smartphones, and smart glasses, as well as additional industrial IoT devices are participants of modern factory networks and enable shop floor digitalization. These devices produce and consume data and increase network traffic since new applications are installed, which need more data and further devices. Cable-based Ethernet and Wi-Fi are already used on the shop floor to realize networking, shown in Figure 12 below, but they do not meet the requirements for realizing the network for the factory of the future, which needs reliable but flexible networks. Cable-based networks are reliable, but they are not useful for mobile applications, while Wi-Fi is not known for being a reliable technology. In contrast to these, Light Fidelity (LiFi) and 5G are very promising technologies for realizing the network for the factory of the future with reliable wireless communication between fixed and mobile devices across the factory network at moderate data rates and low latencies. Scenarios for the application of LiFi and LiFi with 5G in factories are described in the next section.

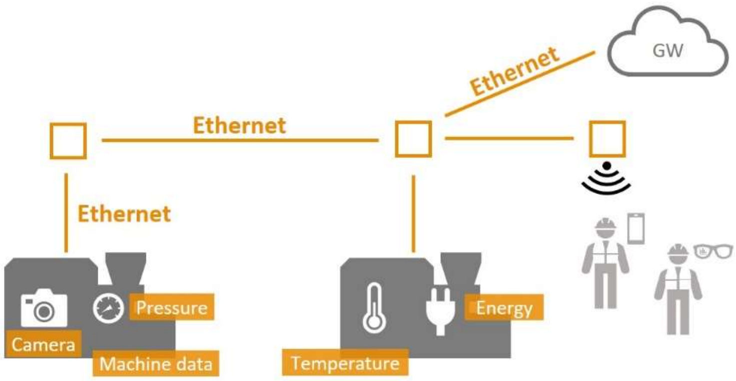

Figure 12: Communication on the shop floor via cable-based Ethernet and WiFi

4.5.1. Functional characterization

Figure 12 illustrates that machines are connected with a factory network across cable-based Ethernet to ensure reliability and mobile devices that are connected via Wi-Fi to ensure mobility. This scenario requires many Ethernet cables and many Wi-Fi access points (AP) for coverage, and the network infrastructure is not flexible because it needs regularly modifications when machines are regularly moved on the shop floor. In the publications [2] and [3], scenarios for the application of LiFi in factories and a system architecture for LiFi with 5G are described. These scenarios are shown in Figure 13, Figure 14, and Figure 15 all indicating the potentials of LiFi for factory networks.

Application scenario 1: "LiFi cells for wireless connecting machines"

In Figure 13 machines are wirelessly connected via LiFi cells with the cable-based Ethernet network. In this scenario, LiFi can enable faster start-up for new machines and after relocation of machines because no new network cable must be installed. It avoids the need of cable installation, increases flexibility in case of relocation, and increases security in comparison to Wi-Fi, because the access point is only very locally accessible.

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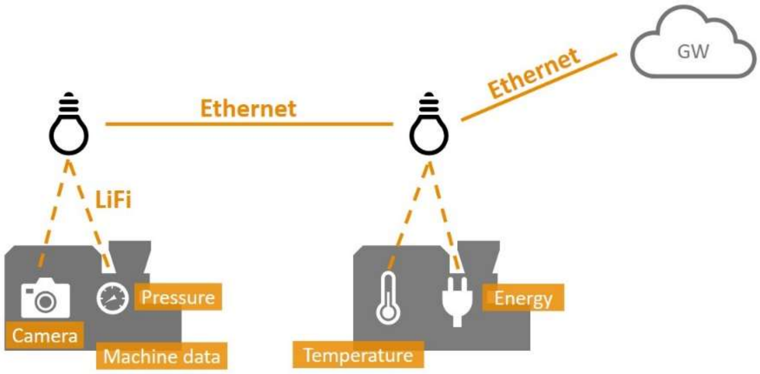

Figure 13: Robust and reliable communication via LiFi cells in IoT network: Machines are wirelessly connected via the lamps of LiFi cells with the cable-based Ethernet network

Application scenario 2: "LiFi for backhaul communication"

In Figure 14, LiFi is used to realize both direct machine connectivity and backhaul communication, whereby often, power-line communication (PLC), plastic optical fiber (POF), or copper-based Ethernet are used for backhauling communication. In this scenario, LiFi can enable faster initialization for new areas on the shop floor because much less network cables must be installed. Through lower efforts of cable installation costs could be reduced. It increases flexibility in terms of installation and makes high data rates available via point-to-point (PtP) connections. Point-to-multipoint (PtMP) communication makes it possible to integrate kind of failsafe.

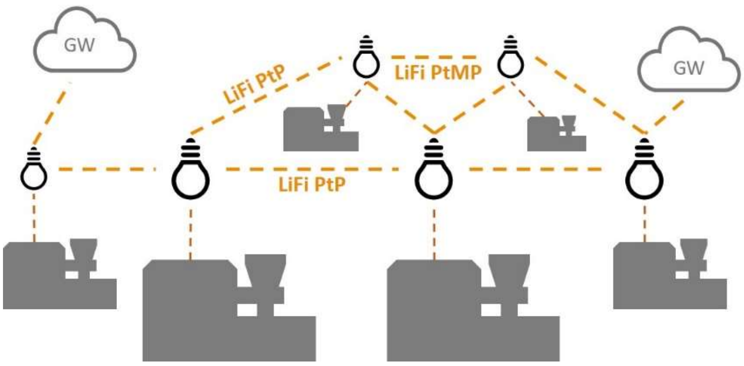

Figure 14: Robust and reliable backhaul communication via LiFi in IIoT network: LiFi cells are connected via point-to-point (PtP) and/or point-to-multipoint (PtMP) connections

Application scenario 3 "Mobility support in IoT networks with LiFi and 5G"

In Figure 15, the two reliable communication technologies LiFi and 5G are combined to enable mobility support. This makes the integration of mobile devices more flexible and enable handover while moving in the factory. In this scenario, 5G new radio ensures coverage within the whole factory while LiFi enables offloading when devices are inside a LiFi cell. This means LiFi serves as an additional access technology to offload certain data streams with requirements for high throughput and low latencies from radio communication, allowing to scale up the number of users per network.

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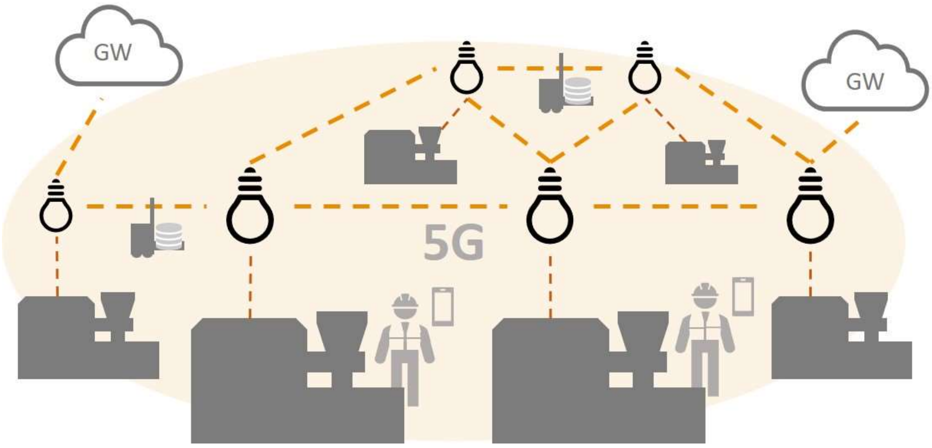

Figure 15: Mobility support in IoT networks with LiFi and 5G

4.5.2. System architecture overview

Factory owners will choose the suitable LiFi solution based on their application needs. In factories where installation of new cabling is not an option, LiFi APs interconnect via optical P2P links to multiple other APs or a gateway. Mesh routing over these links increases resilience against individual link failures.

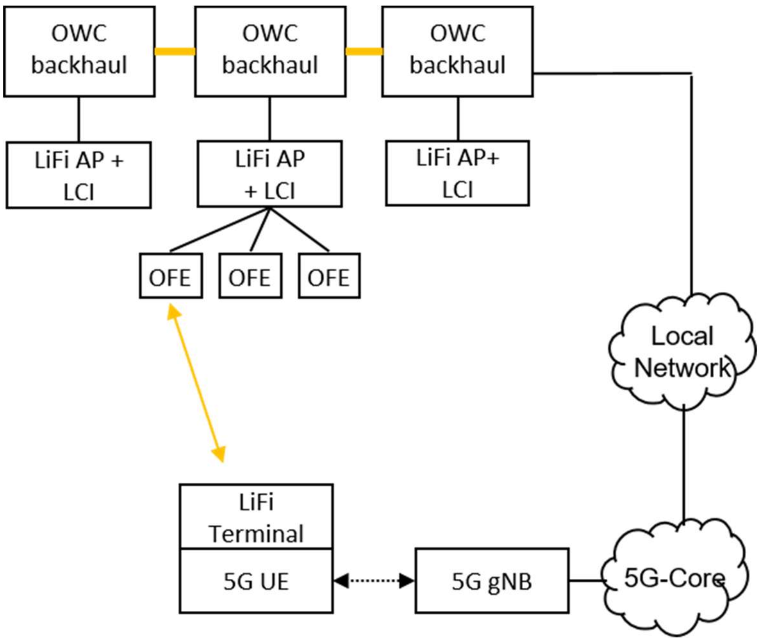

Figure 16: System architecture of industrial communications

Moreover, the distributed MIMO configuration, also commonly used in the office, is deployed for wireless connectivity in applications with higher QoS demands. In contrast to the spatial multiplexing mode used in the office scenarios, the industrial MIMO solution can apply spatial diversity modes, and trade data rate against higher robustness. For mobility support beyond the coverage area of LiFi, industrial IoT devices can favourably combine LiFi with a 5G radio interface allowing for seamless connectivity when devices are used not only in the factory hall with direct LiFi connectivity, but also in other areas like remote places or on the free-air backyard. Figure 16 shows a general version of

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the system architecture for industrial communication leveraging 5G connectivity for the wide area as well.

4.5.3. LiFi industrial communications functional requirements

Multiple LiFi APs are distributed in the manufacturing plant such they can provide seamless coverage for LiFi connectivity and are connected through infrastructure cabling or wireless links providing sufficiently high networking capacity, e.g., throughput, latency.

LiFi must enable connectivity of devices through association of a unit with the network like what is known from Wi-Fi regarding access control, authentication, and authorization. In particular, LiFi has to allow to set up traffic specifications, regulating the QoS requirements of all data flows originating from the unit or going towards the unit.

LiFi should further provide management and adapted allocation of communication resources due to mobility. Handover and interference between adjacent LiFi APs must be addressed as well as different channel characteristics, i.e., LoS and NLOS. In addition, sufficient robustness for industrial communication must be ensured while considering the directivity of light. Scalability of the communication system with respect to the size of the covered area must be facilitated.

4.6. Digital Life Door lock, Control Access

4.6.1. Functional characterization

Mobile access is becoming commonplace: the user gets access to a facility by sending a request to an electronic lock. The lock recognizes the request, verifies the provided access code, and opens up. Current radio frequency- based communication technologies such as Wi-Fi, near-field communication (NFC), and Bluetooth are applied in a large variety of applications. However, they have serious security drawbacks: The data can be picked up by devices within a 10-meter radius, they are susceptible to hackers, consume substantial amounts of power, are not interoperable with all operators and platforms and usually require costly hardware.

LiFi-based door lock solution, shown in Figure 17, can provide secure mobile access through photonics without any of the drawbacks when compared to available mobile access solutions. It can be used on any mobile device as all smart phones already have the required hardware components. There are three steps: 1) download and activate an app to a smart phone, 2) introduce personal profile and 3) trigger the screen light and modulate an optical custom code.

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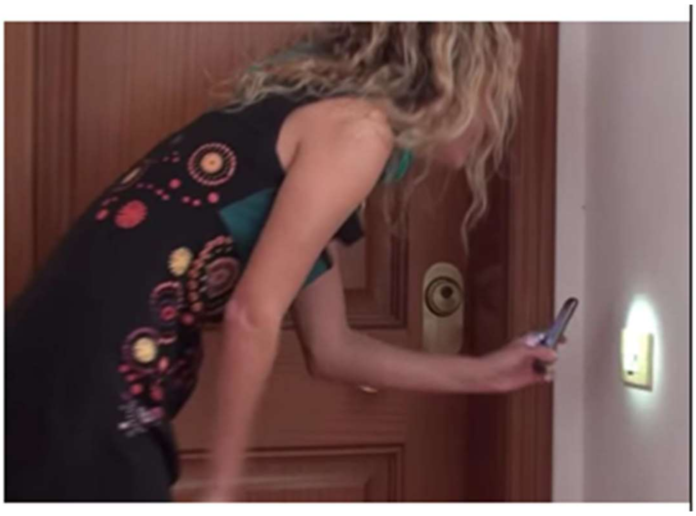

Figure 17: Digital Life Door lock, Control Access

The LiFi door lock product Figure 18 is very powerful and at the same time made by low-cost technology that can be adapted to grant secure access permission by using merely mobile devices with performance similar to the intrusive and expensive NFC and RFID technologies. The set consists of a control unit, optical receiver, mobile application, and uses a standard electronic lock.

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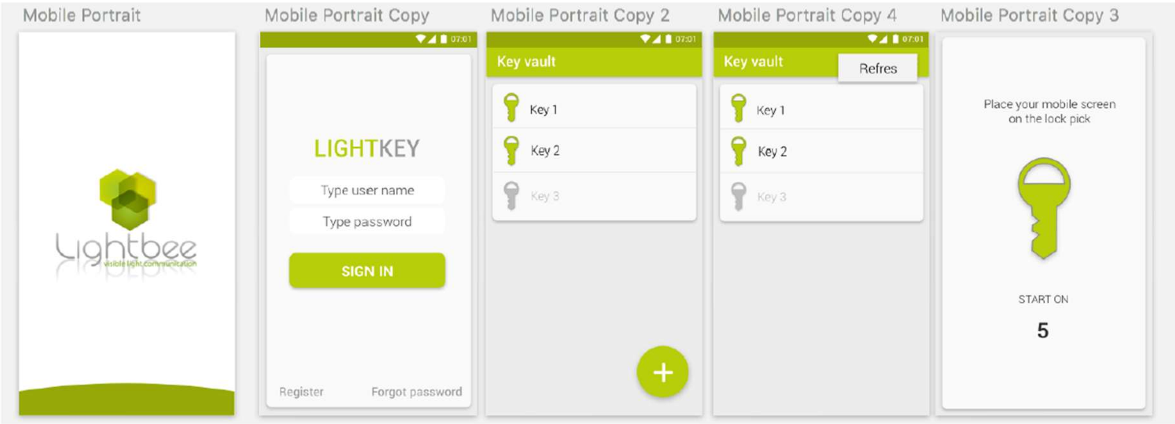

Figure 18: The LiFi-based door lock product

As there is an increasingly urgent need for authenticated entrance, and the universal integration of mobile devices in our society is observed. The LiFi door lock has the ability to meet the broad range of innovative customers of the Access Control Market: Commercial companies and independent users (hotels, residential complexes, condominiums, car makers), and any other customers where security is a top priority (hospitals, banks, government). Figure 19 shows the architecture of the control access platform that is used for the digital door lock.

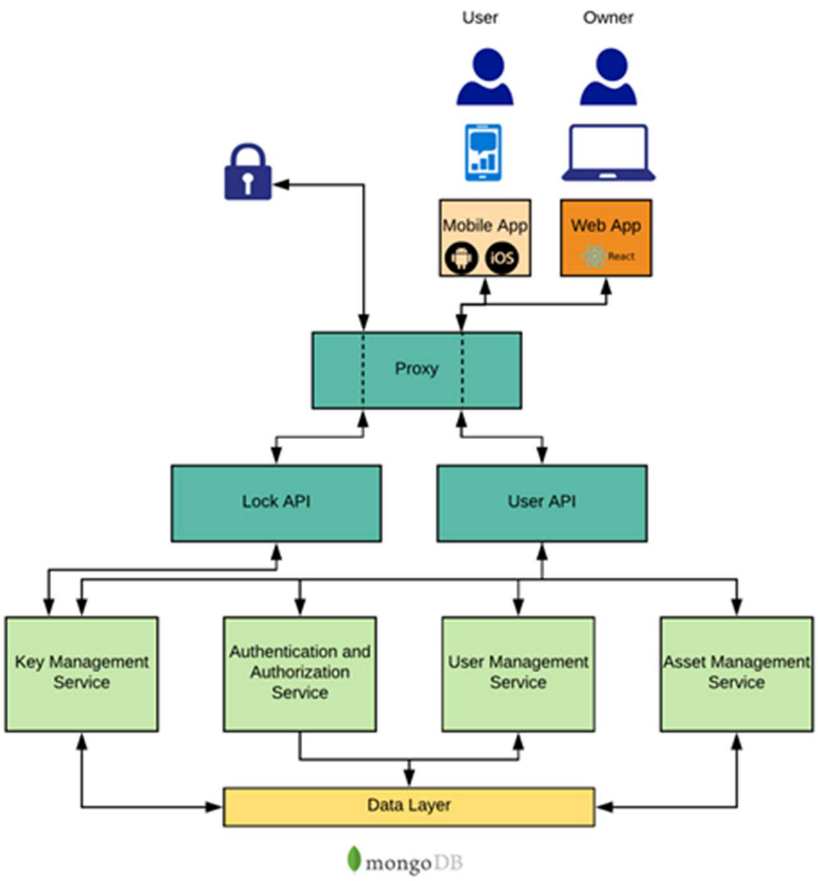

Figure 19: Control access platform architecture

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4.6.2. System architecture overview

First of all, there is the upper layer that is formed by the applications that request and use keys. This layer is composed of the Lock Firmware application, the LightKey mobile Apps and the LightKey Web Application, developed using React.js. The next layer is the API layer. It is formed by two different APIs, the Lock API, and the User API, that offer the necessary endpoints for delivering all the requested functionality to the Application layer. The Service layer contains a set of services that are consumed by the API layer and contain all the necessary business logic. This includes authentication, authorization, users, keys, and asset management. Finally, the data layer is composed of a MongoDB repository and the Software layer managing the access to this data repository.

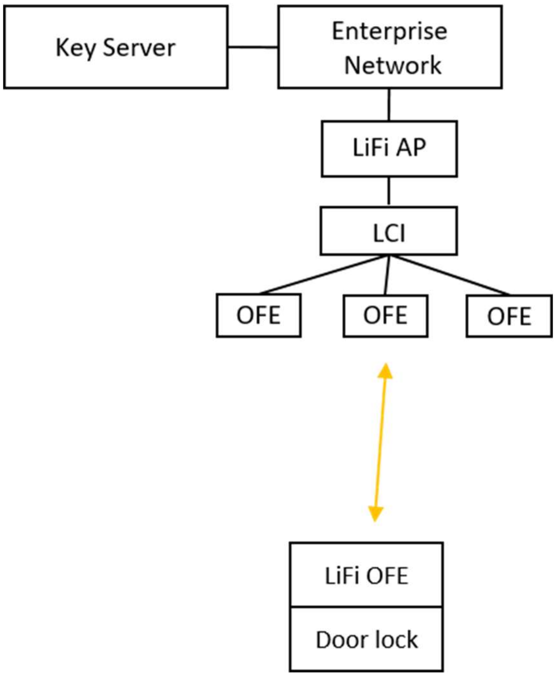

Figure 20: System architecture of Digital doorlock

The system architecture as seen in Figure 20 describes the use of a low data rate LiFi link in order to connect the door lock to the Key Server through the LiFi Access Point and the Enterprise network. In this case communication from the door lock to the access point can be made unidirectional if the keys are saved in the lock or bidirectional if a complete control access procedure is needed. Obviously, in the second case more energy is needed from the batteries to send the access code and to get the response with an open or not command.

4.6.3. LiFi Digital Doorlock functional requirements

The main functional requirement of the complete system is low power consumption. In this demonstrator the controller in the door lock is sleeping till the user wants to open the door. In that moment, all the electronics systems wake up and recognize the code from the user and start the comparison, in key saved mode, or start the communication if the keys are not saved in local electronic. In this second case a transmission must be made by the door lock to the access point.

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This transmission must be low data rate and with a short frame in order to consume as less power as it can. Even in the reception stage a low power receptor must be used for energy-efficient purposes.

4.7. Digital Signage

4.7.1. Functional characterization

Digital Signage is used in many industries with the most prominent and eye-catching being retailers who use it within store windows or to promote special offers and stock. However, schools, colleges, universities, local councils, hospitals, and other businesses around the globe also use signage to provide staff communications messages, information for guests and visitors or a branded TV channel.

Here are just a few examples of using digital signage in business nowadays.

- **Retail**. Retail digital signage allows businesses to efficiently and effectively reach and interact with their customers. Uses for digital signage include attracting new business, increasing brand awareness, improving operating efficiency, catching the attention of the public, promoting new products, and enhancing customer experiences.
- **Corporate Communications.** Digital signage can be used for everything from greeting customers when they enter the lobby of a business to informing and motivating employees.
- **Entertainment.** From theatres and amusement parks, uses for digital signage in the entertainment industry are almost boundless. Digital signage is used to display ticket prices, update show times, offer special promotions and reinforce customer loyalty.
- **Healthcare.** Conveying critical information while keeping patients and their visitors at ease and reinforcing patient confidence are among the uses for digital signage in the healthcare industry.
- **Education.** Today’s students have been living in a digital world since a very early age. Digital signage in education spaces have been used via kiosks for finding one’s way around campus, class and test date schedules, cafeteria menu boards and sending emergency alerts and special event notices to students.
- **Outdoor Advertising.** Although outdoor advertising has been around for years, digital signage takes it to a whole new level. It eliminates the printing, installation and updating expenses associated with billboard advertising. By rotating them, multiple advertisements can be delivered on a single digital sign. Messages can also be varied by the time of day or day of the week.
- **Government.** Government uses digital signage for alerting the public to emergencies, crime alerts and disaster information. Digital signage can also improve interoffice and interagency communications, as well as wayfinding for visitors to government buildings or parks.

Instead of a dedicated copper cable or RF link through the installations, optical wireless communication can send the data from the media server to every media player in the digital signage network. In this case, a lamp near the screen can transfer data or messages to the player that controls the screen in a wireless way without losing QOS. In this use case, the downlink link must be

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in VLC while the uplink must be in IR to not disturb the audience. In the same manner, the server can be connected to the distribution network through a LiFi link. In Figure 21 a digital signage system is shown.

Figure 21: Digital Signage system

4.7.2. System architecture overview

The typical Digital Signane system can be seen in Figure 22. It is based on a Media Server that stores multimedia content and can be updated through different clients. The content is sent to the players via the enterprise network and then a wired or wireless link can be used to connect the players. The main purpose of this demonstration is to replace cables or WIFI links with a LiFi IR link to update the content in the players. In this case, LiFi coverage islands can give flexibility to the system in order to position the players and the screens. As can be seen in Figure 22 different optical front-ends could be used to extend the coverage area of the system. AS WIFI links could be saturated in some environments this solution could help to have dedicated links in the Infrared light spectrum.

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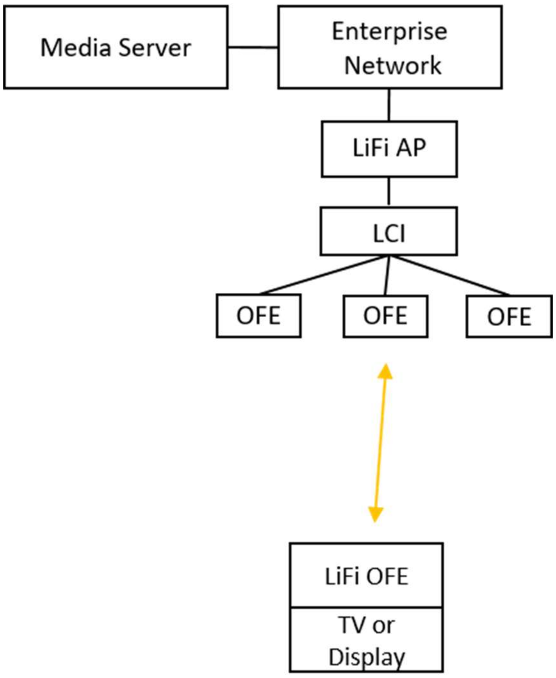

Figure 22: System architecture of Digital Signage

4.7.3. LiFi Digital Signage functional requirements

As in the consumer home use case, to transport the data traffic from the media server to the LiFi hotspots some sort of infrastructure is needed. The main option is the Ethernet infrastructure that the building must have. Obviously, PLC or POF could be used, but taking into account that this type of application is used in big buildings, it is supposed that a structured cabling was previously installed. AS it was said in the system architecture the coverage area of the LiFi link will give some freedom of positioning to the player and even the screen but the power plug in the electrical installation can hinder the position of the multimedia screens.

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5. LiFi open reference architecture

5.1. Overview

The LiFi open reference architecture will be introduced in this chapter in a structured stepwise approach. After defining the scope of the LiFi open reference architecture within the common end-to-end data communication infrastructure, and introducing the basic terminology used for the description, a basic model with functional entities, and interfaces and reference points will be presented. Subsequent the basic model is extended for additional functions like access point functionality, fronthaul, and MIMO. Putting the pieces together in a comprehensive reference architecture concludes the chapter.

5.1.1. Scope of reference architecture

Various reference architectures exist in communications. The LiFi open reference architecture is aimed for providing a common model for the specific part in the overall end-to-end communication architecture that the deployment of LiFi as over-the-air interface introduces between the terminal at the user side and the access network on the infrastructure side.

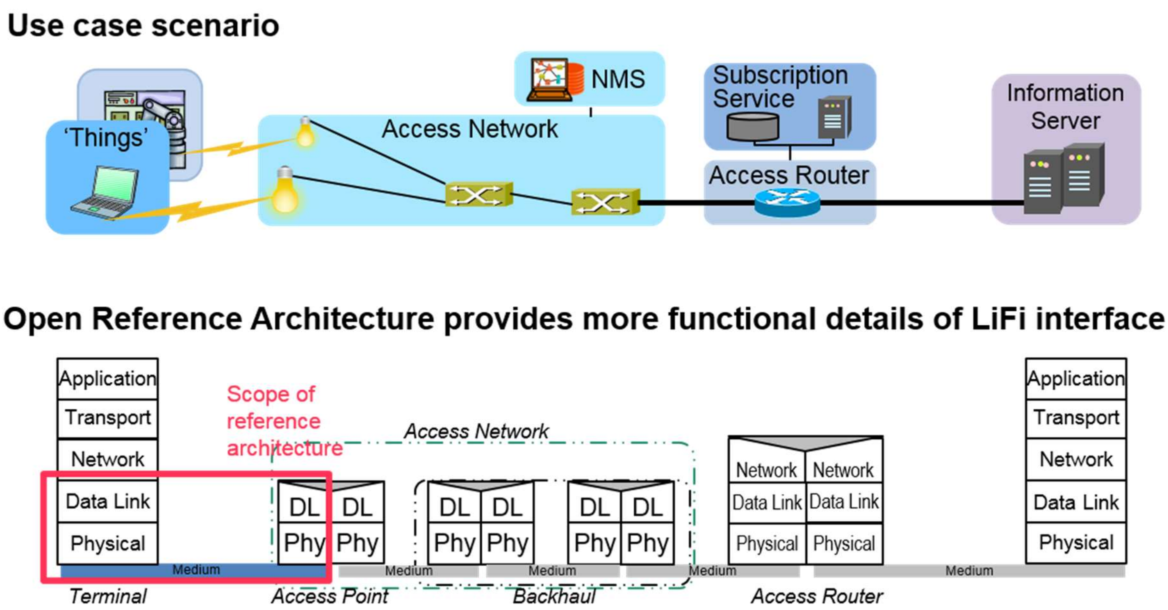

Figure 23: Scope of reference architecture in end-to-end communication architecture

The scope of the LiFi open reference architecture is depicted in the Figure 23 above. As indicated through the red rectangle, usage of light instead of radio waves for the link over the air impacts the PHY and the Data Link layer at both the terminal and the access point. LiFi can completely replace radio communication interfaces, and the replacement mostly does not cause any changes in the rest of the communication architecture except some parameters in the network configuration and management system (NMS).

5.1.2. Basic terminology

The following terminology is applied for the specification of the LiFi open reference architecture and the description of the various extensions and application scenarios:

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- Terminal
  - It denotes the entity containing the endpoint of communication towards the user
- Access Point
  - It denotes the entity that provides wireless communication to one or more terminals incorporating at least one LiFi interface
- LiFi interface
  - It denotes the PHY and DL layer functionalities that are required to realize communication over light
  - A LiFi interface consists of
    - Data Link layer
    - One Modem that executes the signal processing functions required for the PHY
    - One or more Optical Front End (OFE)
- Optical Front End
  - Part of the LiFi interface that converts (digital or analogue) electrical signals into optical signals
- Fronthaul
  - It denotes a communication system connecting distributed OFEs with the Modem.

5.1.3. Mobility terminology

To maintain connectivity while moving terminals across areas covered by wireless access networks the terminal must dynamically change its point of attachment potentially even through changing the network interface used for communication.

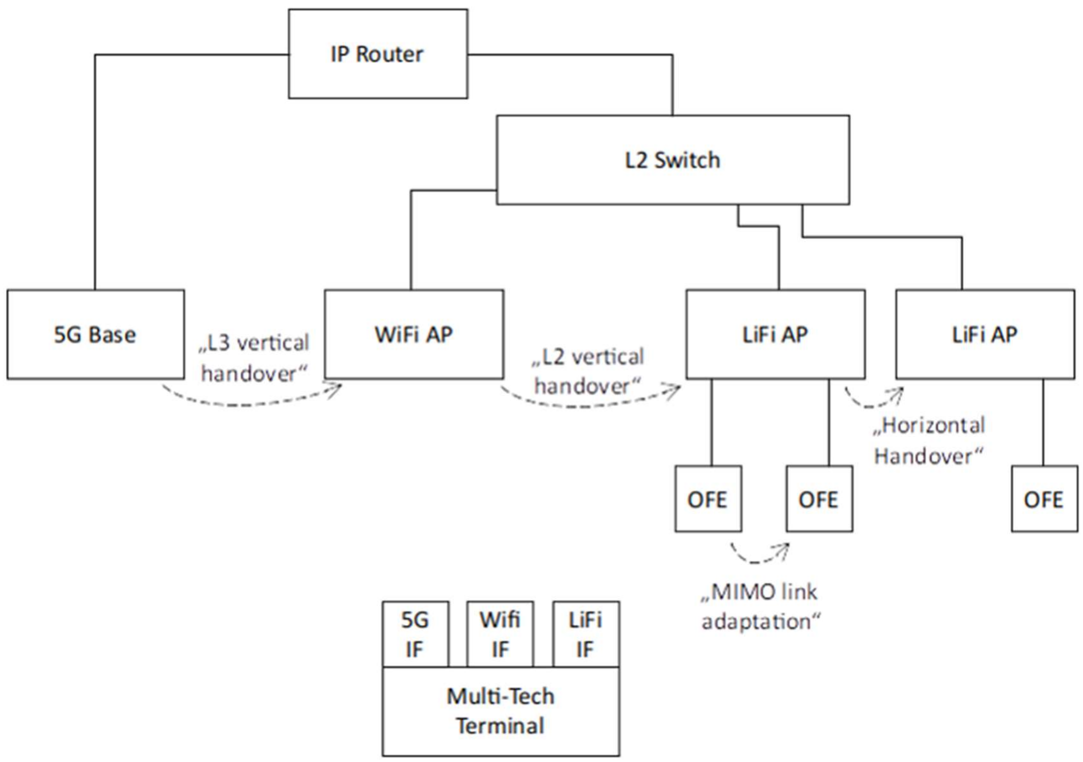

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Figure 24: Mobility scenarios

Depending on the network arrangements various transition schemes between nodes of attachment to the access infrastructure could happen as depicted in the Figure 24 above. The table below lists and explains the terms used to denote the various schemes.

Term	Description / definition
Vertical L3 handover	The routine facilitated to move IP-level connectivity of a terminal between a completely different access technology and a LiFi network. The terminal's IP address might be preserved.
Vertical L2 handover	The routine facilitated to move layer 2 connectivity between a Wi-Fi network and a LiFi network. The terminal's MAC address is preserved.
Horizontal handover	The transfer of association state between two neighboring, possibly coordinated, APs. This is independent of the interference coordination facilitated between the APs.
MIMO link adaptation	The (antenna selection / MIMO scheduling / …) of a single AP with multiple optical frontends to aid a terminal's mobility. All association state remains in the AP.

Table 1: Mobility terminology

Orthogonal to the list of transition schemes listed above is the distinction between hard handover and soft handover:

- Hard handover, aka 'break-before-make'
    - The connection between the terminal and the serving access point is teared down before the (re-)establishment of the connection to the target access point. It usually causes longer periods of interruptions of the connectivity
- Soft handover, aka 'make-before-break'
    - The terminal establishes the connection to the target access point before tearing down the connection to the serving access point. Considerably shorter interruptions result from soft handover but require more complex signalling schemes at the terminal and the access network, as both the network as well as the terminal must be capable to handle two session contexts.

Note: *Due to its seamless nature, MIMO link adaptation is often considered as a kind of soft handover. Effectively, it does not require two session contexts, as the transition is accomplished by MIMO functions in the PHY without impact to the session state maintained in the Data Link layer.*

5.2. Basic reference architecture

The basic reference architecture model is depicted below. It is closely aligned with the common layered ISO-OSI open systems interconnection model [4] that established the basic architectural model of all modern communication systems.

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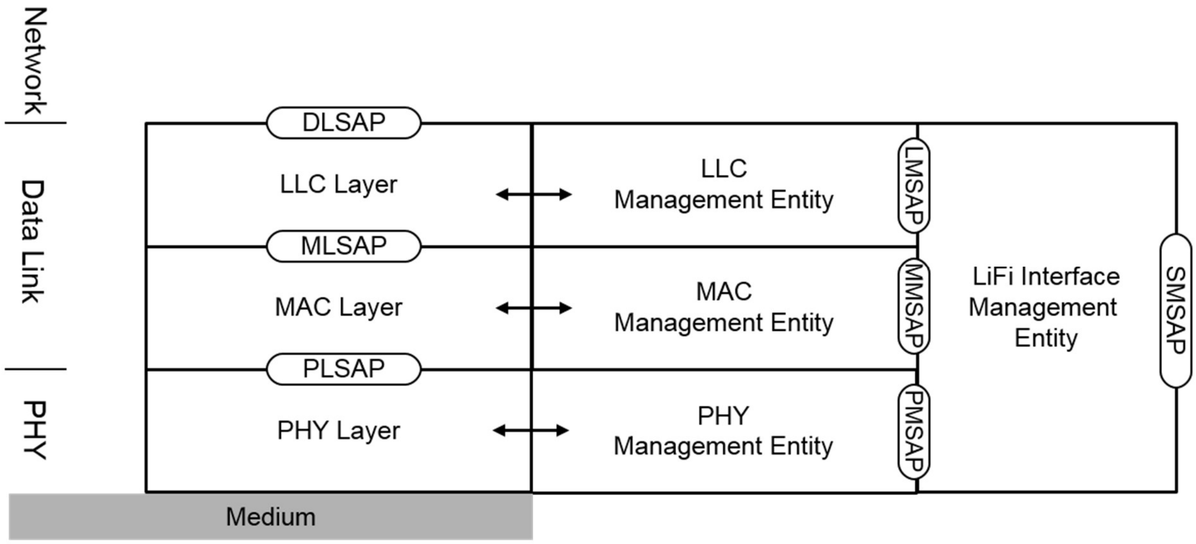

Figure 25: Basic reference architecture

The reference architecture covers the Data Link layer and the PHY layer of the open system interconnection model. The Data Link layer model is divided into sublayers comprising the medium specific functions in the MAC layer, and the link control functions in the LLC layer.

All layers have their related management entities and overall coordination and control across all layers is performed through the LiFi interface Management Entity that provides the service access point for the control of the LiFi interface through external control and management entities.

5.3. Core functional entities

The functional behaviour of the LiFi interface is structured through three functional layers, each with its own management entity and a common system management entity that provides a common external management interface and control across the three layers. Each layer does not only communicate locally with its management entity, but also exchanges control and management information with its peer through layer-specific header information.

5.3.1. Functional entities of LiFi interface

The LiFi open reference architecture comprises the following functional entities:

- PHY (Physical) layer
    - The PHY layer comprises the functions to encode and modulate protocol data units delivered by the MAC layer into a stream of physical signals for transmission over the medium, as well as the functions to demodulate and to decode physical signals received over the medium and to forward the reconstructed data frames into the MAC layer for further processing.
    - Depending of the procedures for controlling the access to the medium, the PHY can also perform sensing of the medium to detect clear channel conditions.
- PHY management entity
    - The companion entity to the PHY layer comprises the management functions to tune behaviour and parameters of PHY layer in order to increase performance and efficiency of the coding and modulation process.

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    - It provides services for PHY layer configuration and monitoring to the LiFi interface Management Entity.
- MAC (Medium Access Control) layer
    - The MAC layer comprises the functions to control and perform the transmission of higher layer protocol data units over a shared medium.
    - It contains the basic access mechanisms to coordinate and control the access to a shared medium; provides the capabilities for fragmentation, reassembly, and retransmission of user data into entities suited for transmission over the medium, and it performs the ciphering algorithms so enable secure transmissions over a shared medium.
- MAC management entity
    - The companion entity to the MAC layer comprises the management functions to establish and maintain the MAC operations.
    - It provides functions to establish synchronization among units sharing the same medium, to perform power management through identification of idle periods and hibernation of power consuming processing functions, to pursue scanning processes in the medium to learn about usage and potential peer partners, to establish, maintain, and teardown associations with peer partners, and to provide capabilities for external MAC configuration and monitoring of the MAC layer.
- LLC (Logical Link Control) layer
    - The LLC layer comprises the functions to perform secure and authenticated forwarding of network layer protocol data units across established communications links provided by the MAC layer.
    - It contains the port access entity controlled through the authentication process that securely gates that data exchange to the peer device and the protocol discrimination and encapsulation functions to allow multiplexing control as well as various higher layer protocols on the communication link established with the peer entity.
- LLC management entity
    - The companion entity to the LLC layer comprises the management functions for the establishment and maintenance of secured and authenticated links with peer communication partners.
    - It executes the authentication procedures and takes care for the management of the encryption keys, which are applied through the ciphering function in the MAC layer.
- LiFi interface management entity
    - The LiFi interface management entity covers the system management functions of the whole LiFi interface and interacts with the PHY management entity, the MAC management entity, and the LLC management entity to operate the LiFi interface for transmission of user data through light to another device.
    - In addition to initiation and configuration of the entire system, it provides monitoring data of the various layers to an external network management system.

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5.3.2. Communication with peer entities through layered header information

Each layer communicates with its peer entity through information that is prepended to the layer's service data unit and forwarded as protocol data unit to the lower layer for transmission over the medium.

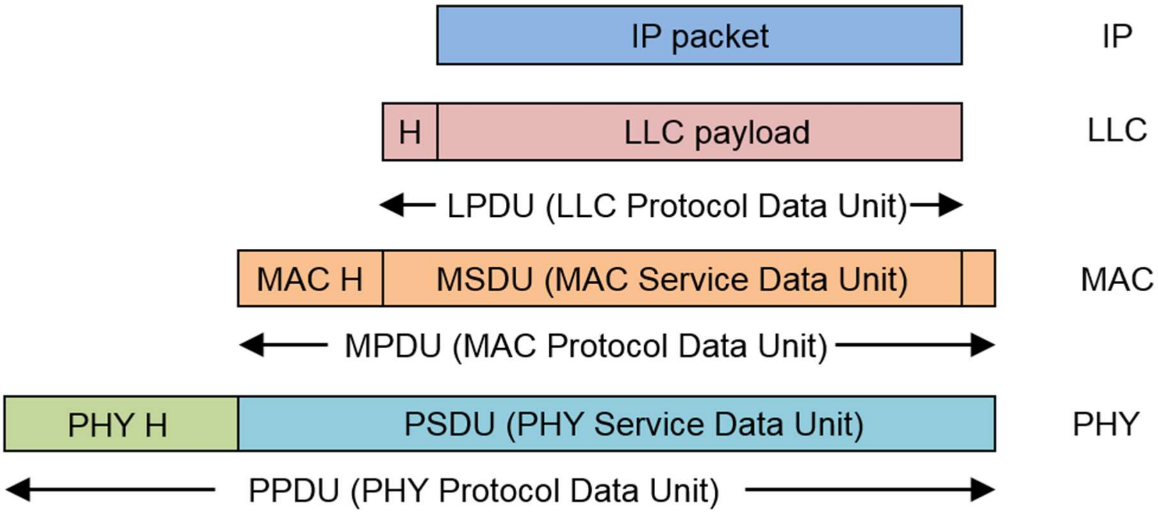

Figure 26: Protocol data unit concatenation through successive preceding of header information

The Figure 26 shows the concatenation of the PHY protocol data unit that is transmitted over the medium through prepending header information of each of the layers of the reference architecture. Depending of the actual implementation of the PHY, the PHY layer may be divided into a PHY convergence sublayer and a PHY layer to enable easier adoption of different coding and modulation techniques within a single system design.

5.4. Interfaces and reference points

Communication of user data through light communications from one peer to another peer is performed by cooperation of the entities of the open reference architecture across interfaces between the entities. These interfaces are denoted as reference points, or service access points.

The Figure 27 depicts all reference points that are usually defined in LiFi interface specifications. The interface between the LLC Layer and LLC Management Entity, as well as the MAC Layer and the MAC Management Entity, and the PHY Layer and the PHY Management Entity are only indicated by arrows below, but are not explicitly denoted, as they are usually kept implementation specific and are not detailed in communication interface standards. Similar, the interface between PHY Layer entity and MAC Layer entity is not exposed below, as the two functional entities are highly integrated with each other in modern system designs to enable performant and cost-effective implementations.

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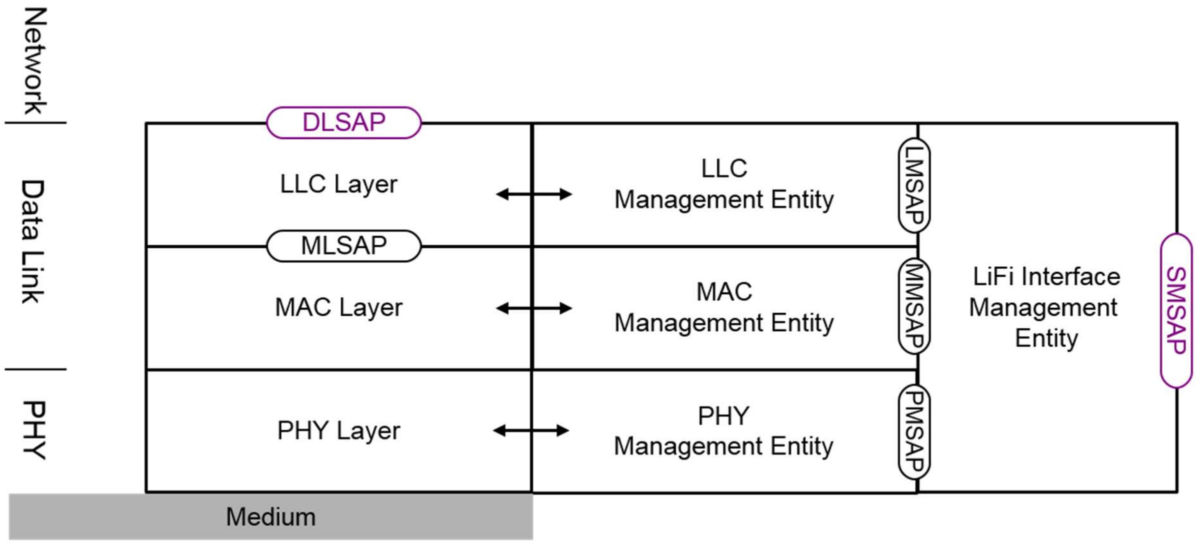

Figure 27: Open interfaces in reference architecture model

Out of the six denoted reference points of the LiFi open reference architecture, four reference points are internal to the LiFi interface and mostly important only to the chip implementers of a LiFi interface standard. There is no need to establish open reference points for these internal interfaces, but informative descriptions of the usual functions provided is helpful for better understanding of the behaviour of different solutions of LiFi interfaces.

The two external reference points DLSAP, and SMSAP are highlighted through purple colour as they are important to system developers and integrators, who deploy LiFi technologies in their system implementations. Open specifications of the external reference points foster interoperable LiFi interface specification and facilitate easy adoption of LiFi to system designs, as system integrators can chose among the most appropriate LiFi interface designs without expensive adaptations of the end-to-end systems.

5.4.1. Internal reference points (informative)

The MLSAP in the datapath, as well as the management interfaces PMSAP, MMSAP, and LMSAP are internal interfaces of the LiFi open reference architecture. The list below provides some information about the nature and exemplary functions of these interfaces.

- MLSAP (MAC Layer Service Access Point)
    - MAC layer data interface towards the Logical Link Control layer for retrieving and forwarding MSDU.
    - Usual functions provided by this SAP:
        - Forwarding of transmission frames downstream
            - MA-UNITDATA_request/_confirm
        - Forwarding of transmission frames upstream
            - MA-UNITDATA_indication
- PMSAP (PHY layer Management Service Access Point)
    - Layer management interface for PHY layer functions
    - Usual functions provided by this SAP:

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        - Reset of the PHY layer configuration and state to default
            - PM-RESET_request
        - Configuration of operational parameters of PHY layer
            - PM-ATTRIBUTE_request/_confirm
- MMSAP (MAC layer Management Service Access Point)
    - Layer management interface for MAC layer functions
    - Usual functions provided by this SAP:
        - Reset of the MAC layer configuration and state to default
            - MM-RESET_request/_confirm
        - Configuration of operational parameters of MAC layer
            - MM-ATTRIBUTE_request/_confirm
        - Perform scanning procedure to detect available communication peers
            - MM-SCAN_request/_confirm
        - Establish association with communication peer
            - MM-ASSOCIATE_request/_confirm
        - Communication peer requests an association
            - MM-ASSOCIATE_indication/_response
        - Re-establish association with another peer (handover)
            - MM-REASSOCIATE_request/_confirm
        - Communication peer requests the re-establishment of an association
            - MM-REASSOCIATE_indication/_response
        - Tear down association with communication peer
            - MM-DISASSOCIATE_request/_confirm
        - Communication peer requests the termination of an association
            - MM-DISASSOCIATE_indication/_response
        - Set the ciphering key of an association
            - MM-SETKEYS_request/_confirm
        - Erase the ciphering key of an association
            - MM-DELETEKEYS_request/_confirm
        - Establish a traffic stream with QoS parameters
            - MM-ADDTS_request/_confirm
        - Communication peer requests a traffic stream with QoS parameters
            - MM-ADDTS_indication/_response
        - Tear down an established traffic stream
            - MM-DELTS_request/_confirm
        - Communication peer requests to terminate an established traffic stream
            - MM-DELTS_indication
        - Time synchronization for spatial reuse
            - MM-TIMESYNCHRO_request/confirm
- LMSAP (Link layer Management Service Access Point)
    - Layer management interface for Logical Link Control layer functions
    - Usual functions provided by this SAP:
        - Perform EAP over LAN procedure

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        - LM-EAPOL_request/_confirm
    - Initialize key renewal cycle of communication peer
        - LM_PEERKEYSTART_request

5.4.2. Open interfaces

The LiFi open reference architecture provides two open interfaces, the DLSAP for the transmission of user data frames, and the SMSAP for the system configuration, control, and management of the LiFi interface.

- DLSAP (Data Link Service Access Point)
    - Data path interface of the LiFi interface towards the network layer
    - Functions provided by this SAP:
        - Transmission of a user data frame to the communication peer
            - DL-UNITDATA_request/_confirm
        - Receipt of a user data frame from the communication peer
            - DL-UNITDATA_indication
- SMSAP (System Management Service Access Point)
    - Management and control interface of the LiFi interface
    - Functions provided by this SAP:
        - Reset the LiFi interface to default state with data path disabled
            - LFI_CMD_RESET.
        - Enable and manage LiFi physical interface
            - LFI_CMD_GET_WIPHY,
            - LFI_CMD_SET_WIPHY,
            - LFI_CMD_NEW_WIPHY,
            - LFI_CMD_DEL_WIPHY.
        - Enable and manage DLSAP interface
            - LFI_CMD_GET_INTERFACE
            - LFI_CMD_SET_INTERFACE,
            - LFI_CMD_NEW_INTERFACE,
            - LFI_CMD_DEL_INTERFACE.
        - Scan for potential communication peers
            - LFI_CMD_GET_SCAN,
            - LFI_CMD_TRIGGER_SCAN,
            - LFI_CMD_NEW_SCAN_RESULTS.
        - Connect and manage connection with communication peer
            - LFI_CMD_CONNECT,
            - LFI_CMD_ROAM,
            - LFI_CMD_DISCONNECT
        - Authenticate and encrypt connection to communication peer
            - LFI_CMD_AUTHENTICATE,
            - LFI_CMD_DEAUTHENTICATE,
            - LFI_CMD_SET_PMKSA,

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- LFI_CMD_DEL_PMKSA,
- LFI_CMD_FLUSH_PMKSA,
- LFI_CMD_PMKSA_CANDIDATE.

- Set transmission class and transmit data frame
  - LFI_CMD_ADD_TX_TS,
  - LFI_CMD_DEL_TX_TS,
  - LFI_CMD_SET_QOS_MAP,
  - LFI_CMD_FRAME,
  - LFI_CMD_REGISTER_FRAME,
  - LFI_CMD_FRAME_TX_STATUS.
- Synchronization and timing
  - LFI_CMD_SET_SYNCHRO
- Vendor proprietary command
  - LFI_CMD_VENDOR.

5.5. Extensions

The LiFi open reference architecture described above is limited to simple, single input single output peer-to-peer communications over light. For the intended use cases in the domain of IoT higher requirements to the functional capabilities of LiFi interface exist.

The following subsections describe extensions to enhance the basic LiFi open reference architecture for access point operation, the deployment of fronthaul to serve widely distributed light emitters and receivers through a single processing unit, the deployment of multiple input multiple output technologies to increase throughput and coverage of a LiFi interface, and to retrieve positioning information through the LiFi interface.

5.5.1. Introduction

The demanded functional extensions amend additional refinement and functional building blocks to the open reference architecture. For explanation, the additional functions are shown in the data path portion of the reference architecture. Each additional function introduces amendments as well to the layer management functions and the system management interface.

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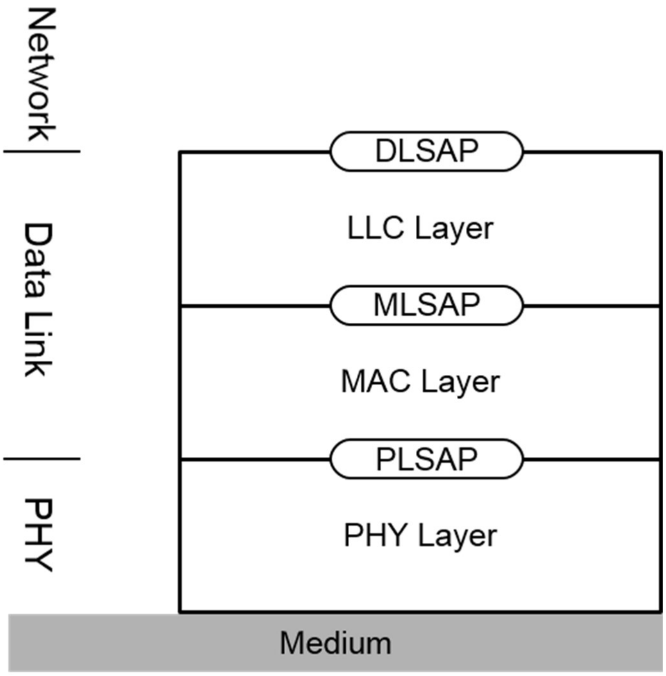

Figure 28: Datapath section of basic open reference architecture

The Figure 28 shows the datapath of the basic reference architecture. It is used in the following sections to display the various amendments to the basic reference architecture to realize the additional functions required for successful deployment of LiFi for IoT applications.

5.5.2. Access Point

Infrastructure operations of LiFi requires point of attachments to the infrastructure that can handle multiple terminal connections in parallel. For serving multiple concurrent connections through a single device the LiFi interface needs to be enhanced to maintain multiple sessions in parallel, and to forward user datagrams according to the destination address through the connection established for the related terminal. To route user data packets accordingly, a bridging function is added directly below the DLSAP leading to an LLC layer that provides a virtual port for each of the associated terminals. Such bridging function for handling multiple concurrent L2 connections is called 'portal'. Effectively, it establishes an instance of a LLSAP data path interface for each of the connected terminals.

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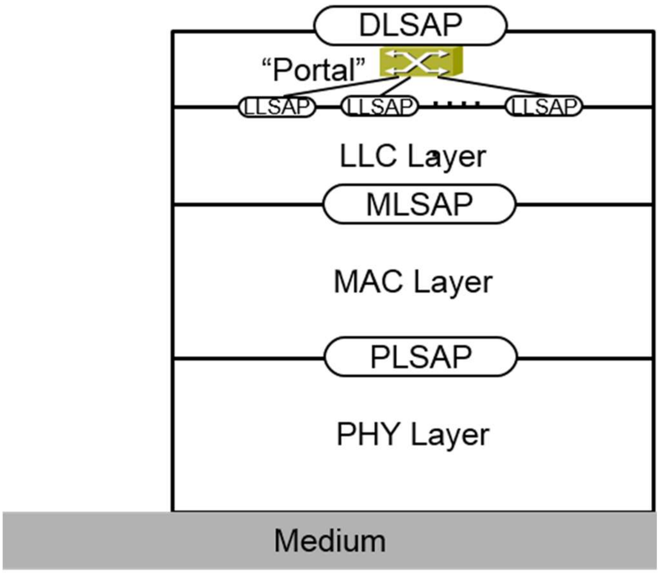

Figure 29: Link layer extensions for AP functionality

The Figure 29 depicts the amendment of the portal resulting in multiple instances of LLSAPs beneath a common DLSAP, which is able to retrieve and forward user data frames to multiple communication peers over LiFi. Forwarding can either happen according to MAC addresses (bridging) or through routing, that assigns a network layer address to each of the connected terminals.

Several additional system management commands are amended to the SMSAP interface to facilitate the external control of the AP operation.

- AP extensions to SMSAP
  - Additional commands to facilitate control of AP operation
    - Perform environmental sensing for AP configuration
      - LFI_CMD_GET_SURVEY,
      - LFI_CMD_NEW_SURVEY_RESULTS.
    - Set AP and LCS identifier
      - LFI_CMD_SET_APID.
      - LFI_CMD_SET_LCSID
    - Set AP advertisement
      - LFI_CMD_GET_APMARKER,
      - LFI_CMD_SET_APMARKER.
    - Initiate AP operation
      - LFI_CMD_START_AP,
      - LFI_CMD_STOP_AP.
    - Manage connected terminals
      - LFI_CMD_GET_TERMINAL,
      - LFI_CMD_SET_TERMINAL,
      - LFI_CMD_NEW_TERMINAL,
      - LFI_CMD_DEL_TERMINAL.
    - Manage power save operations

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- LFI_CMD_SET_POWER_SAVE,
- LFI_CMD_GET_POWER_SAVE.

5.5.3. Open fronthaul

The PHY layer functionality can be divided into the modem part that transforms the MAC protocol data unit into a sequence of analogue or digital signals for the transmission over the medium or vice versa for the receive path, and into the Optical Front End that converts the analogue or digital output of the modem into light, or light into an analogue or digital signal for the decoding by the modem.

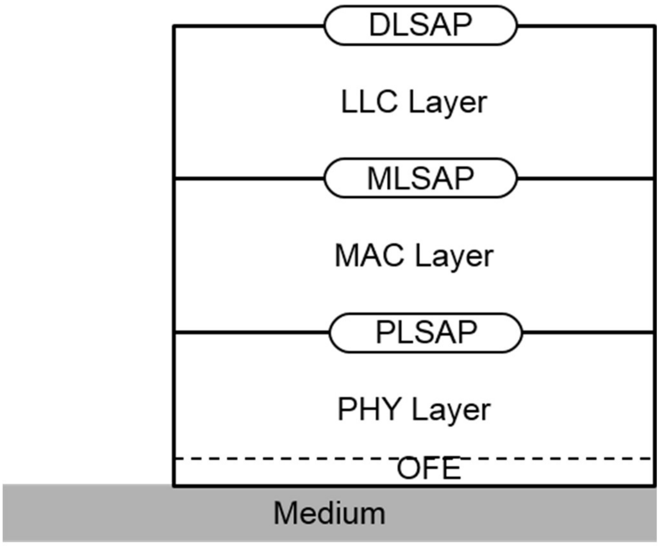

Figure 30: Signal conversion into medium

The Figure 30 illustrates the OFE as the piece of the PHY layer directly interacting with the medium. Often, the OFE is located verynearthe modem circuitry of the LiFi interface with electrical signals directly propagated between the modem and the OFE circuits, i.e., photo diodes and LEDs.

However, sometimes it is desired to locate the OFE in further distance to the modem circuitry to extend the coverage area of a LiFi interface, or to collocate the signal processing of multiple modems in a central processing unit. For these cases it is required to deploy a dedicated communication system called 'Fronthaul' between Modem and OFE to carry the analogue or digital signals of the modem over longer distances. Fronthaul can deploy either digital or analogue transmission of electrical or optical signals.

Open fronthaul is represented in the reference architecture through the exposure of a dedicated interface between the modem part and the optical front end in the PHY layer.

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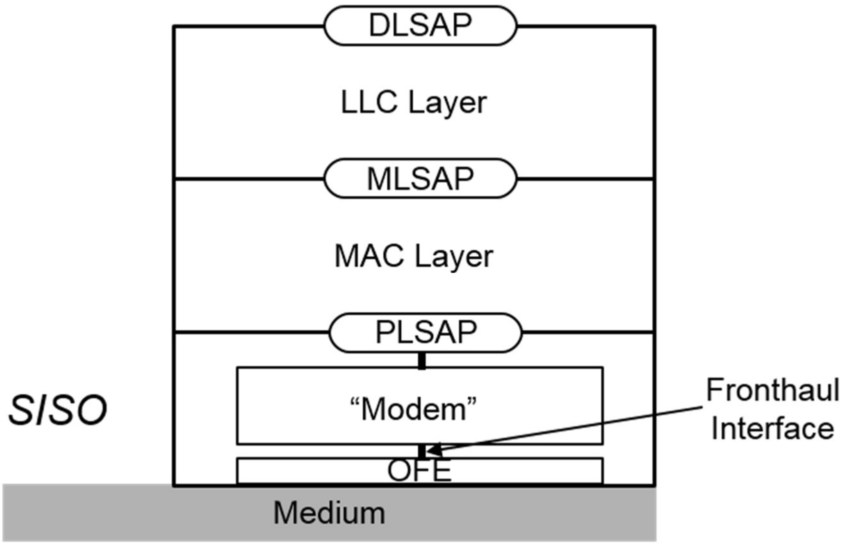

Figure 31: Representation of fronthaul in reference model

It is desired to establish interoperability between different solutions through a specification of the Fronthaul technology applied for LiFi.

5.5.4. MIMO

The application of multiple-input multiple-output (MIMO) techniques is widely discussed within the ELIOT project. As MIMO is around in RF communications since 1990ies, the task for ELIOT is not to develop the technology from bottom up but identify and select promising approaches which imply significant benefits for the deployment of LiFi in practical use cases.

So far, there is no optimal approach for MIMO in LiFi, because of the non-negative and real-valued nature of the intensity-modulation/direct detection (IM/DD) waveform. What is usually done is to apply a positive bias to the waveform and keep the modulation index small compared to the bias, in order to avoid clipping at the zero level. In this way, the LiFi channel can be modelled as a real-valued linear channel with additive white Gaussian noise. As a consequence, the theory of Shannon, which was extended by Foschini and Gans to the case of MIMO can be applied by only considering the real-valued nature of the channel.

More recently, an idea from powerline/phoneline communications was introduced to convert the real-valued channel into a complex valued channel. While a specific form of OFDM (i.e. discrete multitone, DMT) has been discussed since around 2004, originally introduced for LiFi by J. Grubor et al. from HHI, this has led to the conclusion that chipset changes would be needed for LiFi. But one can also apply the so-called frequency up-shift technique used for powerline, coax and phoneline in G.9960. In Figure 32, it is shown how RF waveforms are built together. Note that RF signals are real-valued, too. They are created from a complex-valued IQ baseband signal by up-conversion to the RF centre frequency, which is e.g. 2.4 GHz for Wi-Fi. For Light Communication (LC), which is the term used by IEEE 802.11 for LiFi, one could do the same but use a lower centre frequency around half the system bandwidth. In this way, standard complex-valued OFDM baseband signals commonly applied for RF communications can be applied for LiFi, too.

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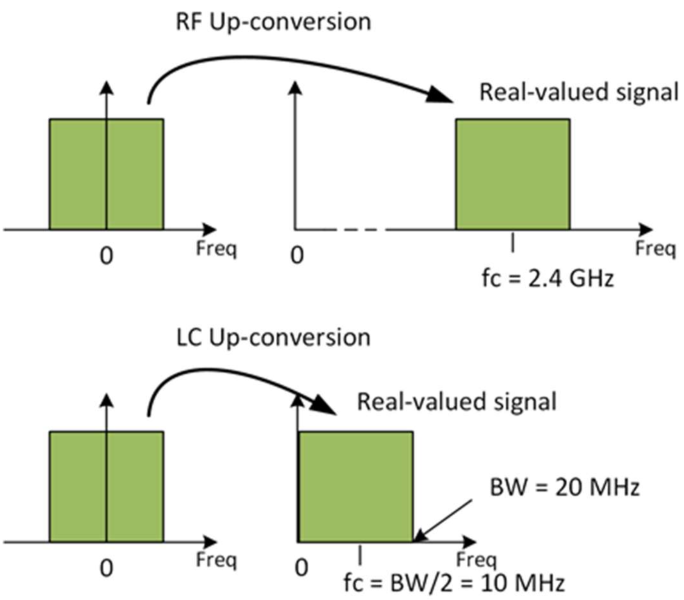

Figure 32: Reuse of existing signal processing schemes from RF for LiFi

With these three assumptions (bias, small modulation index, frequency upshift), LiFi can leverage all existing work for RF MIMO systems, and use the same system models, likewise.

In general, MIMO deploys multiple independent Optical Front-Ends (OFEs) which are functionally used as antennas controlled by a single PHY and MAC layer. Multiple OFEs can be used in diverse ways. In a peer-to-peer topology, see Figure 33, one terminal communicates directly with another terminal or access point. Depending on the numbers of transmitters and receivers one can distinguish single-input single-output (SISO), single-input multiple-output (SIMO), multiple-input single-output (MISO) and MIMO.

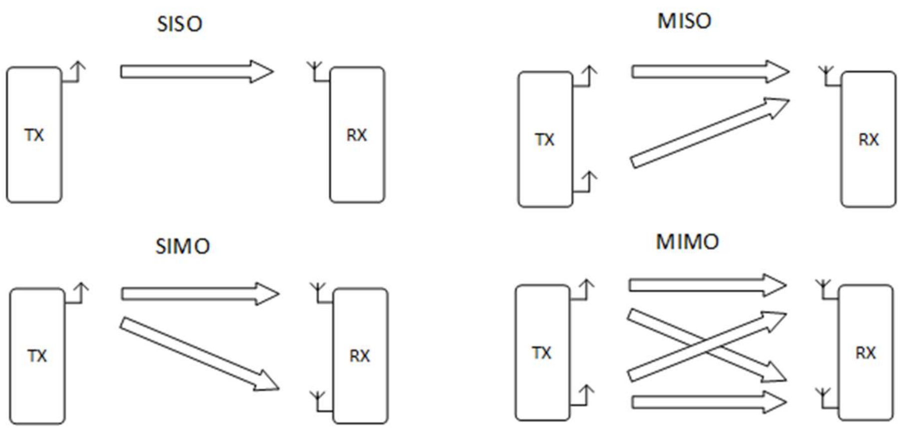

Figure 33: SISO – MISO – SIMO - MIMO

The above notation holds for peer-to-peer topology. MIMO becomes significantly more powerful if multiple terminals are served at the same time from one or multiple access points.

Single-user MIMO supports one or multiple data streams between one access point and one terminal at a time. Multi-user MIMO (MU-MIMO) supports multiple users from a single access point at the same time. Distributed MU-MIMO supports multiple terminals from a single access point at a central

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location and controlling the transmission and reception of distributed antennas or optical frontends in the service area.

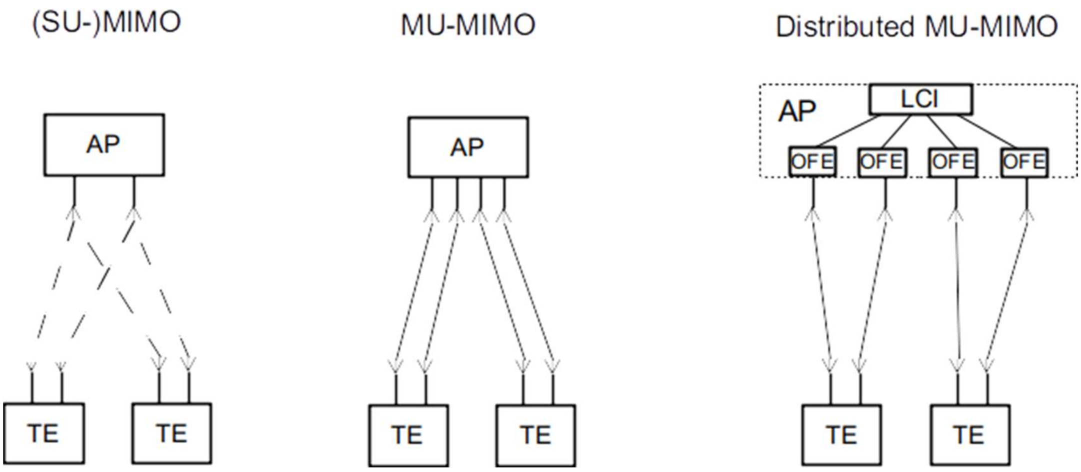


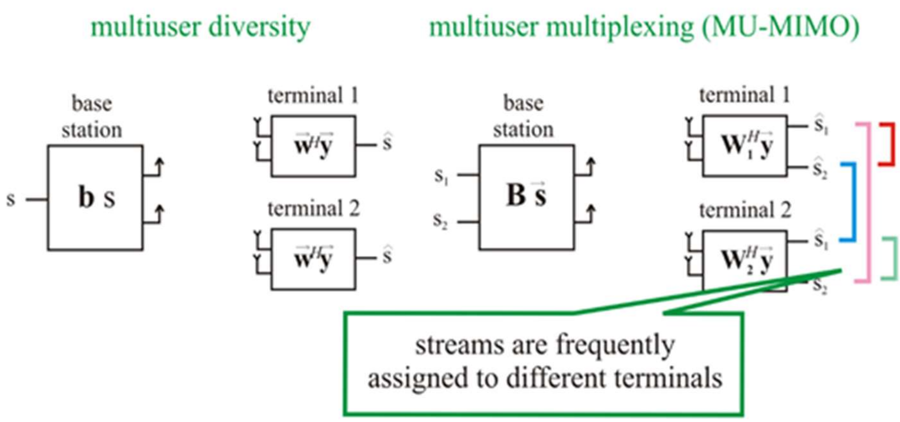
Figure 34: Different configurations when using multiple antennas/OFEs for single and multiple users

For better comprehension, the peer-to-peer configuration is often considered as a special case of MU-MIMO with a single terminal served at the same time , see Figure 34. During connection setup, the terminal which starts the communication assumes the role of an access point. In a different setting at the MAC layer, the role of an access point is manually assigned.

Note that the above notations make no indication at all about the number of data streams transmitted in parallel. All configurations can be used in two different transmission modes

a) spatial diversity: transmitting a single data stream via multiple antennas/OFEs
b) spatial multiplexing: transmitting multiple data streams from multiple antennas/OFEs.

For multiple terminals, the notations a) and b) are changed into multiuser diversity and multiuser multiplexing, respectively.



***Note**: The various possible transmission modes indicated by square brackets.*

Figure 35: Multiuser diversity vs. multiuser multiplexing

Deciding which transmission mode is being used and what combination of antennas/OFEs and users is handled jointly is done in the central medium access (MAC) layer which is a single entity situated in the single access point in any configurations. The MAC layer needs to decide which transmission mode

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(diversity or multiplexing) and what selection of antennas and terminals is best used out of all possible choices, based on feedback information received over the reverse link from all terminals. The optimal MIMO mode selection, and the associated signal processing at the PHY layer, are a coupled NP-hard problem., In order to reduce complexity, several heuristics have been proposed in the literature. These heuristics are called efficient if the performance loss when using them is small but the complexity is significantly reduced compared to the optimal solution.

MIMO operation is reflected in the reference model through multiple OFEs being connected to the Modem part of the PHY layer. The Figure 36 below depicts the extension for the SU-MIMO case with a single data exchange with a peer being executed at a time.

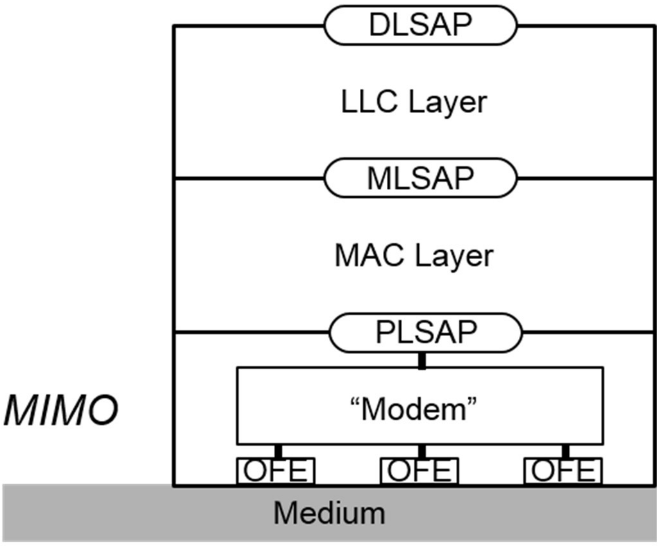

Figure 36: MIMO extension to reference model

In the case of MU-MIMO the reference model is extended to show that the “Modem” provides multiple independent interfaces to multiple OFEs through multiple parallel PLSAPs.

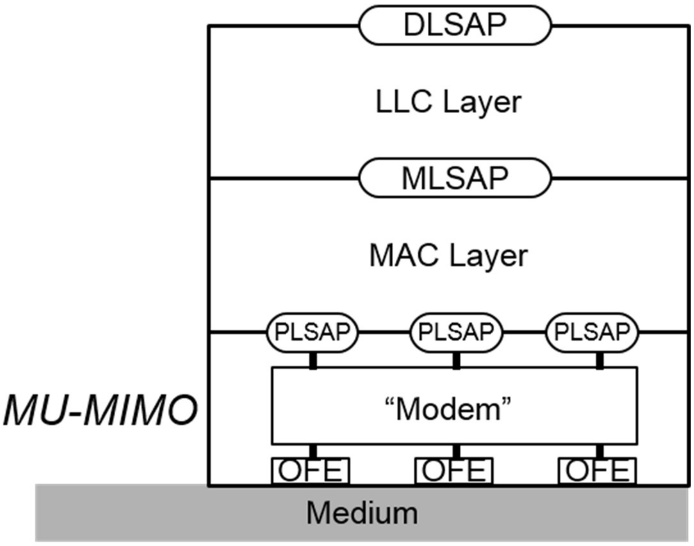

Figure 37: Muli-User MIMO model

In the case of MU-MIMO multiple communication peers can be served in parallel.

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5.5.5. Positioning

Positioning denotes the process of determining the terminal's location through the LiFi system. In general, the availability of LoS signals is beneficial for the achieved location accuracy. Since LiFi relies mainly on transmission via the LoS, accuracies in the range of centimeters are theoretically possible. For positioning with LiFi, OFEs in the ceiling are conceived to serve as fixed reference points for the calculation of the position through multilateration. Other means to gain knowledge about the position are possible but not in our focus.

At the core of the positioning functionality, the distance between the terminal's OFE and each of the ceiling mounted OFEs is determined. To achieve that, the communication protocol employs measurement signals to estimate the time-of-flight between the respective OFEs. From the protocol perspective, two general approaches are conceivable:

1) Unidirectional measurement
2) Bidirectional measurement ("ping-pong")

With unidirectional measurement, a signal is emitted at a well-known time from all transmitters of the infrastructure. Based on the differences in propagation time to a receiver, the position can be calculated (time-difference of arrival "TDoA"). The drawback of this approach is the extremely high required synchronization accuracy of the transmitters. It needs to be below ns, as one ns error time leads to an error in distance of about 30 cm. Therefore, this approach makes primarily sense if the LiFi system employs an analog fronthaul, where the length differences of fronthaul cables is manually compensated, e.g., through a calibration process. Digital synchronization hardly achieves the necessary synchronization accuracy of ceiling mounted OFEs nowadays, although new developments in technology could increase synchronization performance in the future. Therefore, the bidirectional measurement approach ("ping-pong") is preferable and used in this document.

With bidirectional measurements, signals are first transmitted in the one direction, and later in the other direction. E.g., starting with a transmission from the ceiling mounted OFEs to the terminal and finishing with a transmission from the terminal to the OFEs. The benefit is that a fine synchronization of transmitters is not strictly necessary. Instead, the round-trip-time between the OFEs is calculated based on the transmit- and receive time of both transmissions. This allows to perform positioning in a system, where the ceiling-mounted OFEs are connected via a digital fronthaul technology or even part of different LiFi-APs.

The time flow-chart of the bidirectional RTT measurement is shown in Figure 38: Time flow chart of ping-pong implementation. By assuming a reciprocal behaviour of the channel in downlink and uplink, which is not always given for LiFi systems which may use different LED and PD beam characteristics, the exchange starts with the first station sending a ping-packet to the receiver, at the time when the packet leaves the transmitter. Upon reception of initial packet, the second station will generate the pong packet during a known processing time denoted as T_b. After the pong packet arrives back at the first station, the timer will record the received time as T_a. In the last step, the RTT and the distance are estimated based on the following equation:

$$RTT = (T4 - T1) - (T3 - T2) \qquad (5.5.5\text{-}1)$$

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$$d = Tf \cdot c = \frac{RTT \cdot c}{2} \qquad (5.5.5\text{-}2)$$

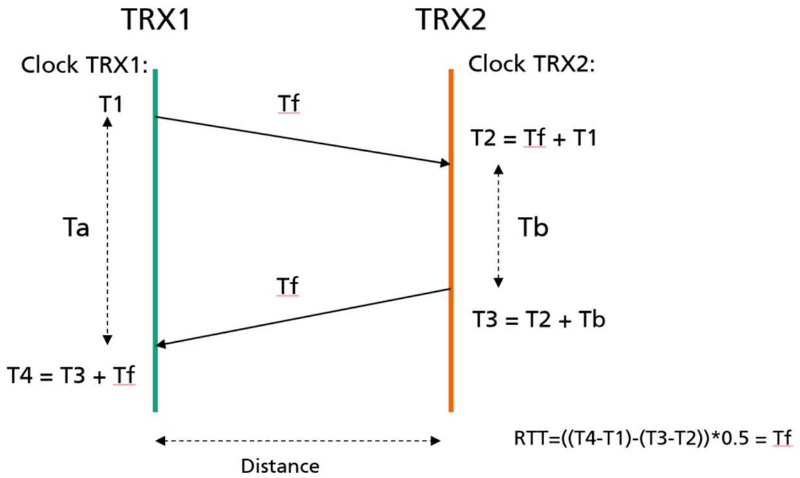

Figure 38: Time flow chart of ping-pong implementation

These elementary steps are usually implemented in the LiFi interface management entity that generates the pilot frames and performs the measurements. Support for positioning does not require amendments to the data path of the reference model, but just adds a few additional system management commands to the SMSAP interface to facilitate the external control of the RTT measurements and to deliver the resulting Tf to an external position process, which performs the higher layer calculations to determine the wanted position out of the measured distances and a-priori knowledge of the geographic locations of the measurement peers.

In the case that positioning is performed on the LiFi terminal, i.e. the terminal likes to determine its location by itself, the positioning process on the LiFi terminal has to query the infrastructure about the geographic locations of the OFEs of the measurement peers. The details of such a higher layer location protocol are out of scope of the Open Reference Architecture.

- Positioning extensions to SMSAP
    - Additional commands to facilitate control of positioning operation
        - Detect peer OFEs that could be used for RTT measurement
            - LFI_CMD_TRIGGER_POS_OFES,
            - LFI_CMD_GET_POS-OFES.
        - Perform RTT measurement and deliver result for particular OFE
            - LFI_CMD_GET_RTT

5.6. Comprehensive reference architecture

All the extensions to the basic reference model introduced in clause 4.5 are completely independent of each other and they can be combined in a comprehensive reference architecture as shown below.

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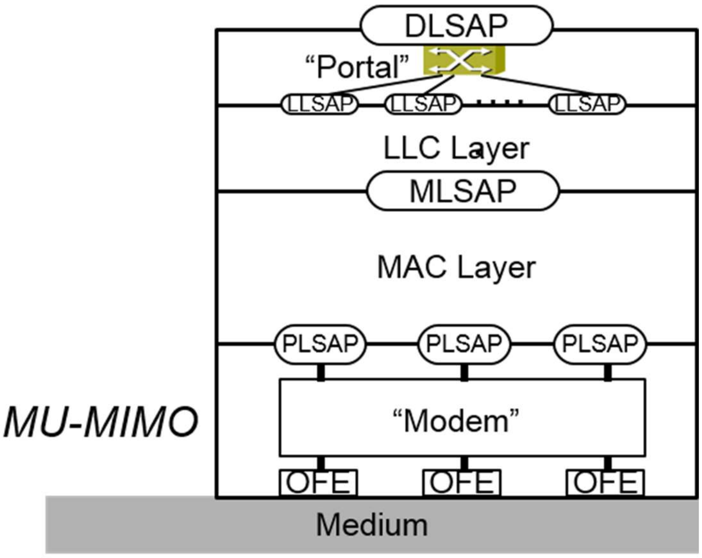

Figure 39: Comprehensive LiFi reference model of data path

The Figure 39 shows the combination of the AP functional extension, exposure of fronthaul interfaces, and MU-MIMO in the data path of the LiFi open reference architecture. Positioning is not yet covered in the model. Furthermore, the management entities of the PHY layer, MAC layer, and LLC layer are missing in the figure, as well as the system management entity with the external control interface of the LiFi interface, but all of them look exactly the same as depicted in the basic open reference architecture in Figure 25.

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6. Relation to standards-specific reference architectures

The LiFi open reference architecture is aimed at providing a common framework for the current light communications standards or standardization projects. This section explains the mapping and close alignment of the ELIOT LiFi open reference architecture with the most evolved LiFi specifications in the industry.

6.1. Terminology mapping

The following table provides the mapping between the terminology used by the ELIOT LiFi open reference architecture and the equivalent terminology used by IEEE 802.11 [5], IEEE P802.15.13 [6], and ITU-T G.9991 [7]. Terms that are not equivalent but still loosely comparable are given in brackets.

ELIOT	**IEEE 802.11** [5]	**IEEE P802.15.13** [6]	**ITU-T G.9991** [7]
LiFi interface	Station	Device	Node
Terminal	Non-AP STA	Device	End point device
Access point	Access point	Coordinator	Domain master (DM)
-	[Portal]	Master coordinator	Global master (GM)
Backhaul	Distribution system (DS)	Backhaul	[Global master]
-	Basic service set (BSS)	Optical wireless personal area network (OWPAN)	Domain
APID	Basic service set ID (BSSID)	OWPAN ID	Domain ID
LiFi Communication Service (LCS)	Extended service set (ESS)	-	-
Optical frontend (OFE)	[Antenna]	Optical frontend (OFE)	-
Fronthaul	-	Fronthaul	-

Table 2: Terminology mapping (Definitions of ELIOT terms are provided in clause 4.1.2)

6.2. Relation to IEEE 802.11 reference model

The basic reference model of IEEE 802.11 that applies also to the amendment P802.11bb for light communications is provided through figure 4-19 of [5].

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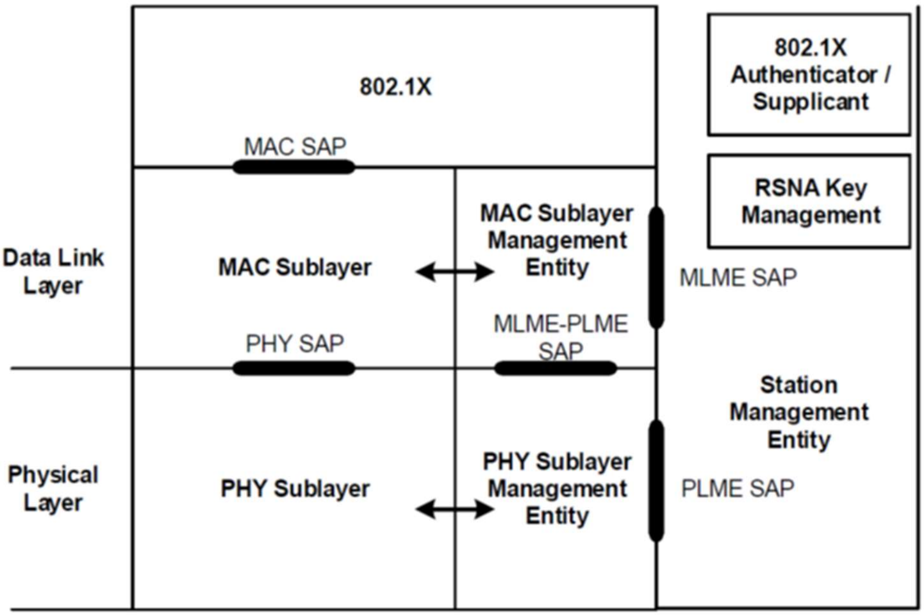

Figure 4-19—Portion of the ISO/IEC basic reference model covered in this standard

Figure 40: IEEE 802.11 reference architecture

The basic reference architecture of IEEE 802.11 is closely aligned to the LiFi open reference architecture introduced above. The models apply the same layering as well as the same functional entities with nearly identical definitions and notations.

A major difference is the existence of open interfaces for system integration. While the LiFi open reference architecture provides open interfaces for the data path as well as the external control and management interface, IEEE 802.11 does not specify either of them. Interoperability of IEEE 802.11 only covers the interface over the transmission medium represented through a set of internal reference points in the architecture, which makes system integration of IEEE 802.11 often a challenge.

To overcome that burden, the LINUX community established a network interface driver project called mac80211 that defines an open approach to the external interfaces of an IEEE 802.11 device deployed within a LINUX based system. mac80211 comprises a common configuration system called cfg80211 that can interact with two variants of implementation of the MAC layer and LLC layer functions. The Full-MAC variant mostly implements all MAC and LLC functions through microcode in the chipset, while the Soft-MAC variant realizes major parts of the MAC and LLC functions through software in the host system with only very time critical processes handled within the chipset.

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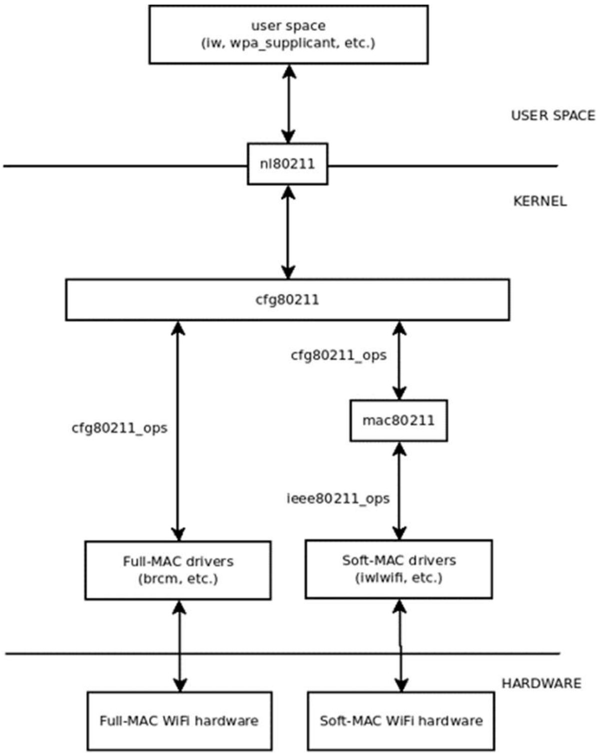

Figure 41: Implementation of IEEE 802.11 within mac80211

For communication between the mac80211 driver that is located in the kernel, and the applications that reside in the user space the interface module nl80211 [8] has been developed and it has become de-facto standard for Wi-Fi configuration in LINUX. The nl80211 is based on the *netlink* protocol for communication between kernel and user space and allows access to most of the PHY, MAC and SME parameters of a Wi-Fi radio interface as defined in cfg80211. Chip vendors have to provide driver code to map their internal data models to the structure defined by cfg80211. By this way, finally an open interface for configuration and management of IEEE 802.11 interfaces has been established. However, it is limited to the deployments within LINUX based systems.

6.3. Relation to IEEE 802.15.13 reference architecture

Even if not immediately apparent, the reference architecture of IEEE P802.15.13 [6] follows also the same approach as the open reference architecture. It is depicted below and shows the same functional entities as defined in the open reference architecture with the major difference that the data path and the management is kept together for each layer, and the device management entity communicates through the MAC layer management entity with the PHY layer management entity.

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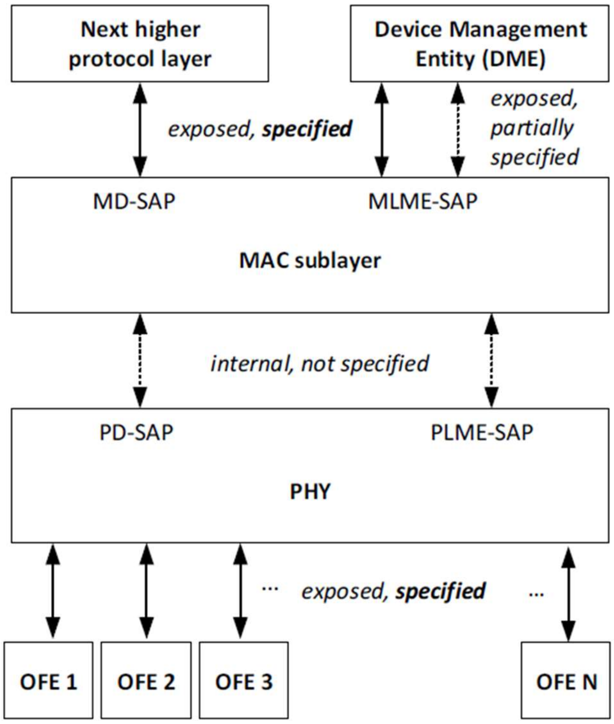

Figure 42: IEEE P802.15.13 reference architecture

Like IEEE 802.11, the IEEE P802.15.13 architecture does not specify external interfaces that are suited for system integrators. Again, the open reference architecture with its open external interfaces and with internal interfaces kept informational does not contradict but nicely complements the P802.15.13 reference architecture.

6.4. Relation to ITU-T G.9991 reference architecture

There is not a single ITU-T G.9991 reference architecture, but four parts that each focus on one single functional aspect. The three functional aspects closely related to the open reference architecture explained below are data path, layer management, and system control and management. The fourth part addresses additional functions required for network integration.

6.4.1. Datapath

The datapath reference model of G.9991 [7] follows the same layering principles applied for the open reference architecture. To allow for highest flexibility regarding the medium used for transmission, and regarding the support of higher layer protocols both the data link layer as well as the PHY layer are divided in three sublayers.

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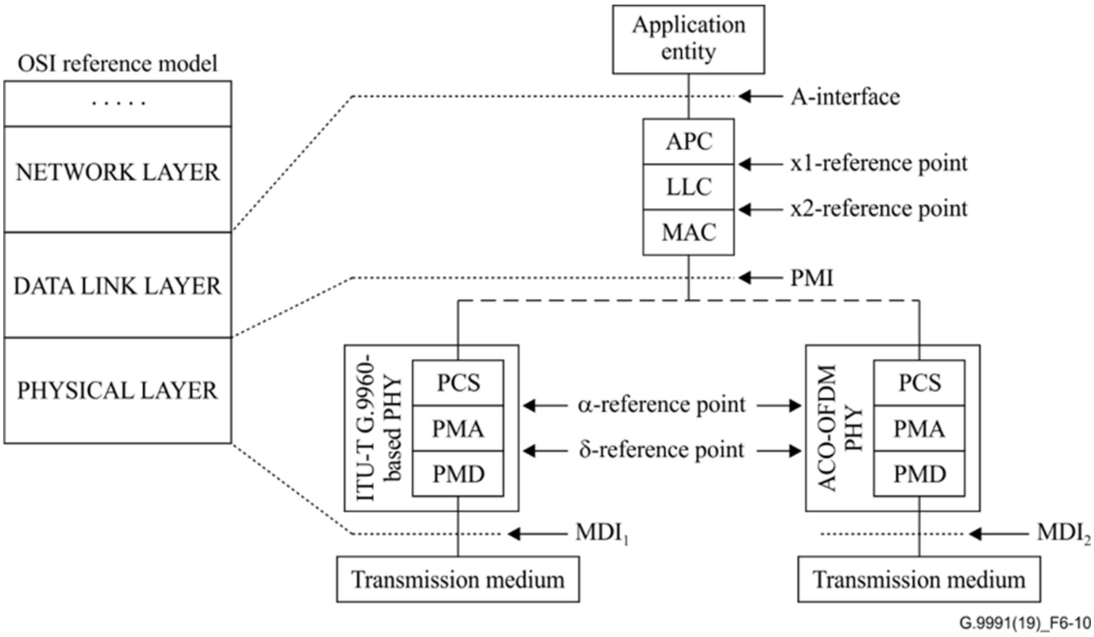

Figure 43: Datapath reference architecture of G.9991

Due to this fine grain sublayering the G.9991 model comprises many more reference points than the IEEE reference models or the open reference architecture to enable higher variability of PHY interfaces as well as support of applications not closely following the ISO-OSI communication model.

6.4.2. Interfaces

The specification of G.9991 defines open interfaces for the data path as well as for the layer management of the Data Link layer as well as the PHY layer. Even when not spelled out in the G.9991 specification, the data primitives establish an interface comparable to the LLSAP, and the control primitives are equivalent to the internal function definitions of the PMSAP, MMSAP, and LMSAP of the open reference architecture.

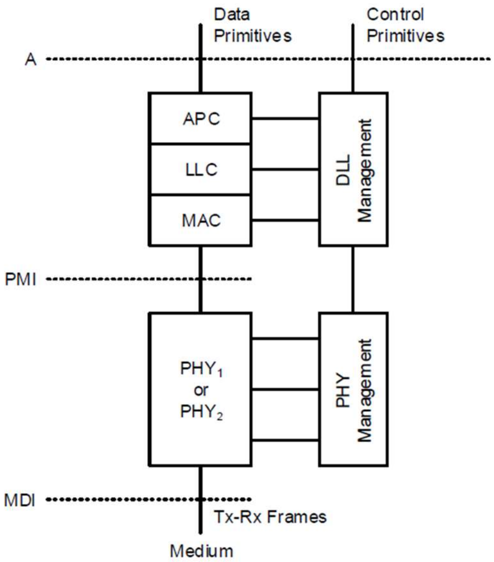

Figure 44: Open interfaces of G.9991

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However, the data primitives as well as the control primitives are differently structured compared to the open reference architecture, but equivalent functionality is available on the interfaces.

6.4.3. Management entity

The G.9991 specification is currently not optimized for deep integration with a host CPU, like in the case of the open reference architecture and the IEEE P802.11bb and P802.15.13 developments. G.9991 assumes solutions are aimed to emulate a standard interface like USB or Ethernet, with a communication interface for control and management.

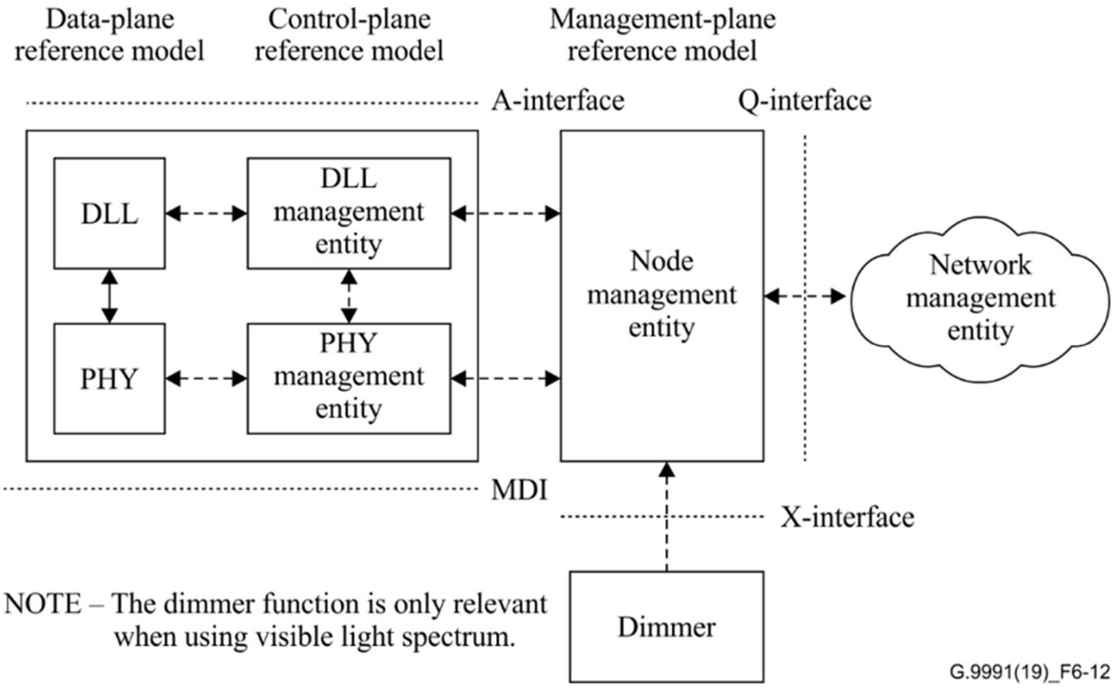

Figure 45: Management model of G.9991

Both, the Q-interface as well as the X-interface could be considered in the scope of the SMSAP of the open reference architecture. It can be expected that conversion between the SMSAP and the Q- and X- interfaces can be accomplished through a management and configuration proxy.

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7. Integration with network reference architectures

While the previous section compared the open reference architecture with the reference architectures of the main standardization projects of light communication interfaces, this section addresses the deployment of the open reference architecture within the network reference models describing the design of IEEE 802 based access networks and the usage of non-3GPP access technologies in the scope of the 5G mobile network.

7.1. Integration of LiFi within IEEE 802.1CF

IEEE 802.1CF [9] provides a network reference model and functional description of IEEE 802 access network. It is defined to cover all the interface technologies developed by IEEE 802 that support the transport of Ethernet data frames carrying MAC addresses as the source and destination address of the layer 2 communication path [10]. Forwarding of the data frames in the network elements along the communication path is performed through bridging as specified in IEEE 802.1Q [11].

The IEEE 802 network reference model denotes by R1 the reference point between the Terminal Interface and the node of attachment (NA) that could be realized through LiFi. The functions comprised in the open reference architecture are embedded in the Terminal Interface as well as in the NA with DLSAP and SMSAP representing internal interfaces of Terminal Interface and NA, respectively. For both Terminal and NA, further processing on top of DLSAP and SMSAP must be present to realize the control interfaces specified for the network reference model. Therefore, the LiFi open reference architecture provides a suited building block that can be well deployed attached to a host computer in access network designs following IEEE 802.1CF.

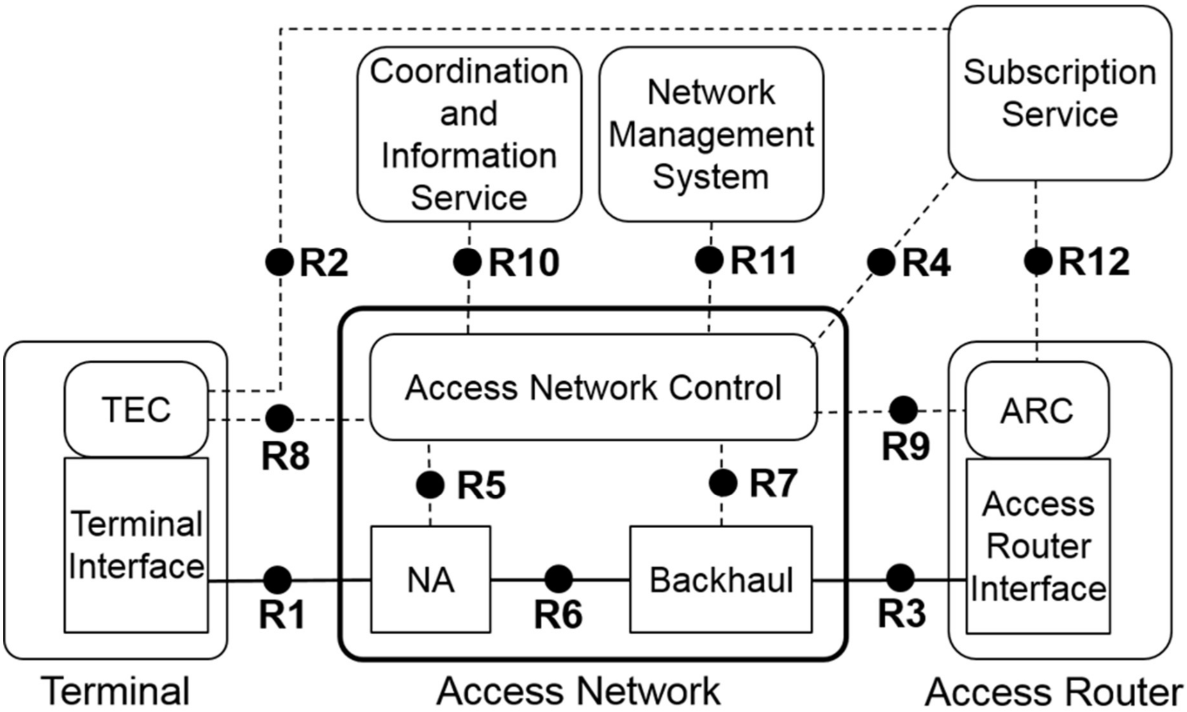

Figure 46: IEEE 802.1CF network reference model

The open reference architecture does not completely cover the NA functions, which are usually implemented in chip sets with the addition of a management entity that is needed to realize R5.

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7.2. Integration of LiFi within TS 23.501

In its TS 23.501 System Architecture for the 5G System [12] specification, 3GPP supplies an architectural concept for deployment of non-3GPP accesses within a 5G system. The approach specified by 3GPP in clause 4.2.8.2.1 of [12] is depicted below.

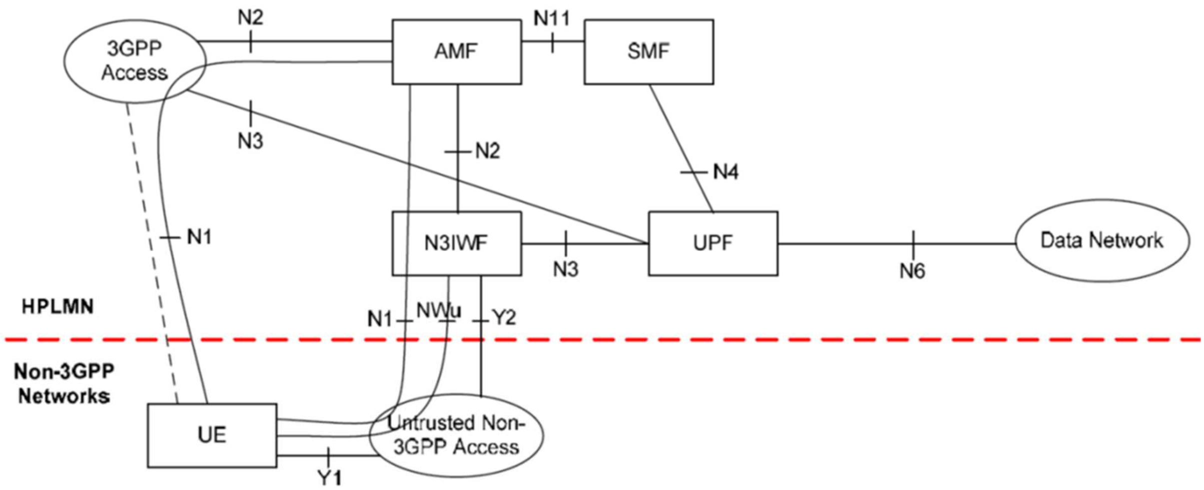

Figure 47: TS 23.501 reference architecture for integration of non-3GPP access technologies

The 3GPP specification does not provide the capability to attach a foreign interface technology to the 5G system but defines the architecture to interwork with non-3GPP networks deploying other kinds of interfaces. Therefore, TS 23.501 assumes that the foreign interface technology is embedded in a non-3GPP access network and only provides the functions to interoperate on network layer and above.

Nevertheless, LiFi can be deployed in a 5G system based on TS 23.501, when the LiFi interface is used by an access network, which e.g. follows the IEEE 802.1CF specification. The IEEE 802.1CF network reference model and functional specification may be leveraged to define the additional functions required to make LiFi working in the TS 23.501 context. IEEE 802.1CF provides on its R3, R4, and R9 reference points the interfaces for the non-3GPP access technology that TS 23.501 expects.

However, the 3GPP interworking model with untrusted non-3GPP accesses lacks the support for QoS support beyond best-effort services. Additional investigations are desired to enable the deployment of the QoS capabilities of LiFi in a 5G system environment.

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8. Reference model software

The LiFi reference software model has the objective to provide a software library to evaluate new functions for the support of mobile IoT devices including an evaluation framework and means for optimization and verification of results. The developed software consists of multiple @Matlab based functions which can be used for several applications like

- LiFi system performance analysis
- LiFi network planning
- Simulations and experiments according to international LiFi communications standards
- Accurate modelling of LiFi channel impairments
- Performance testing
- Interoperability testing
- Hardware verification

Figure 48: Overview LiFi reference software

The main functionalities of the toolbox are:

- IEEE 802.15.13 [6]: PM PHY for OOK
- ITU-T G.9991 G.vlc [7]: PHY for OFDM
- ITU-T G.9960 G.hn [13]: PHY for OFDM
- IEEE 802.15.13 [6]: HB PHY for OFDM
- LiFi channel model

The LiFi channel model allows a frequency domain-based simulation of arbitrary trajectories of mobile users in a LiFi cell with multiple ceiling units. Further aspects like the analog frontend impairments, LOS, diffuse reflection, and blockages are included.

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8.1. OFDM PHY Implementation: ITU-T G.9960 G.hn, ITU-T G.9991 G.vlc PHY 1, IEEE P802.15.13 HB PHY

The PHY implementation for OFDM consists of three major blocks, namely the Physical Coding Sublayer (PCS), the Physical Medium Attachment Sublayer (PMA) and the Physical Medium Dependent Sublayer (PMD) and include adaptive bit- and power-loading of the subcarrier.

The principal structure is shown in Figure 49 and is based on the corresponding standards ITU-T G.9960 [13], ITU-T G.9991 [7], and IEEE P802.15.13 [6].

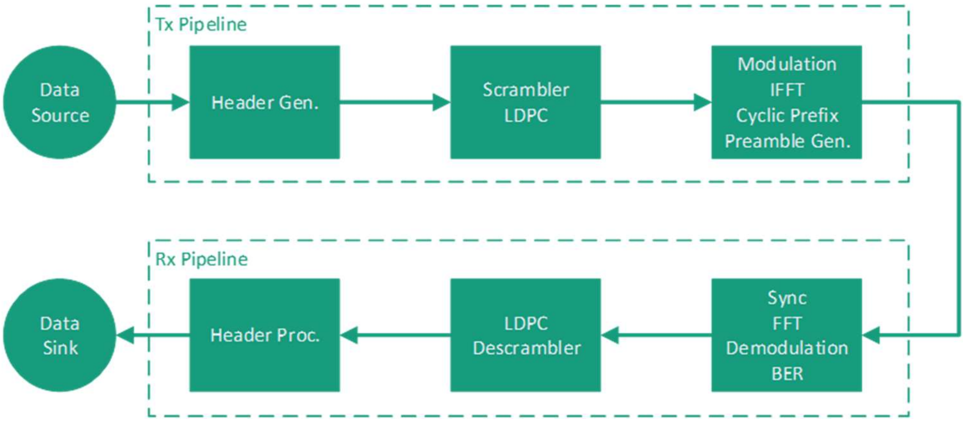

Figure 49: OFDM PHY implementation based on ITU-T G.9960 G.hn | ITU-T G.9991 G.vlc PHY 1 | IEEE P802.15.13 HB PHY standards.

8.1.1. Example of a SISO Ghn based transmission

An example for a single input single output (SISO) transmission for the G.hn PHY using the LiFi toolbox is shown below. The toolbox functions are embedded into a Matlab script and executed in the shown order.

main program (main file for the program execution of SISO G.hn PHY)

ghnPhy_setParameters_siso (signal and channel parameter)

ghnPhy_tx_payloadDataGen (generation of binary input data)

ghnPhy_tx (executes physical coding sublayer (PCS), physical medium attachment (PMA) and physical medium dependent (PMD) sub-layers of the G.hn PHY Tx)

ghnPhy_txPcs (G.hn PHY Tx PCS layer function)

ghnPhy_txPcs_headerGen (generates the header in the G.hn PHY Tx PCS layer)

ghnPhy_txPma (G.hn PHY Tx PMA layer function)

ghnPhy_txPma_scrambler (scrambler)

ghnPhy_txPma_fecEncoder (forward error correction encoder (low density parity check - LDPC))

ghnPhy_txPma_repEncoder (repetition encoder)

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ghnPhy_txPma_blockSegmentation (block segmentation in the G.hn PHY Tx PMA layer)

ghnPhy_txPmd (G.hn PHY Tx PMD layer function)

ghnPhy_txPmd_toneMapper (deserialize and tone mapping)

ghnPhy_txPmd_constMapperScaler (constellation mapper)

ghnPhy_txPmd_constScrambler (constellation scrambler)

ghnPhy_txPmd_ofdmModulator (OFDM modulator (FFT, CP, overlap & add)

ghnPhy_txPmd_preambleGen (generates the preamble in the G.hn PHY Tx PMD layer)

ghnPhy_txPmd_freqUpshift (convert to real-valued baseband)

ghnPhy_ch (channel)

ghnPhy_rx (executes physical coding sublayer (PCS), physical medium attachment (PMA) and physical medium dependent (PMD) sub-layers of the G.hn PHY Rx)

ghnPhy_rxPmd (G.hn PHY Tx PMD layer function)

ghnPhy_rxPmd_frameSync (frame synchronization, Minn or Xcorr based)

ghnPhy_rxPmd_freqDownshift (frequency downshift)

ghnPhy_rxPmd_cpRemove (CP removal)

ghnPhy_rxPmd_fft (FFT)

ghnPhy_rxPmd_ceFde (SISO channel estimation and frequency domain equalizer)

ghnPhy_rxPmd_constDeScrambler (constellation descrambler)

ghnPhy_rxPmd_constDeMapper (demapper)

ghnPhy_rxPmd_toneDeMapper (serialize and tone mapping)

ghnPhy_rxPma (G.hn P HY Rx PMA layer function)

ghnPhy_rxPma_fecDecoder (FEC LDPC decoding)

ghnPhy_rxPma_deScrambler (descrambler)

ghnPhy_rxPcs (G.hn PHY Rx PCS layer function)

ghnPhy_rxPcs_crcDetector (cyclic redundancy check codes)

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8.2. Pulse Modulation PNY Implementation: IEEE P802.15.13

The PHY implementation for Pulse Modulation (or OOK) is structured similarly like the OFDM PHY implementation and consists of header, coding, and a frequency domain equalizer to address channel impairments as shown in Figure 3. It is based on the IEEE P802.15.13 [6].

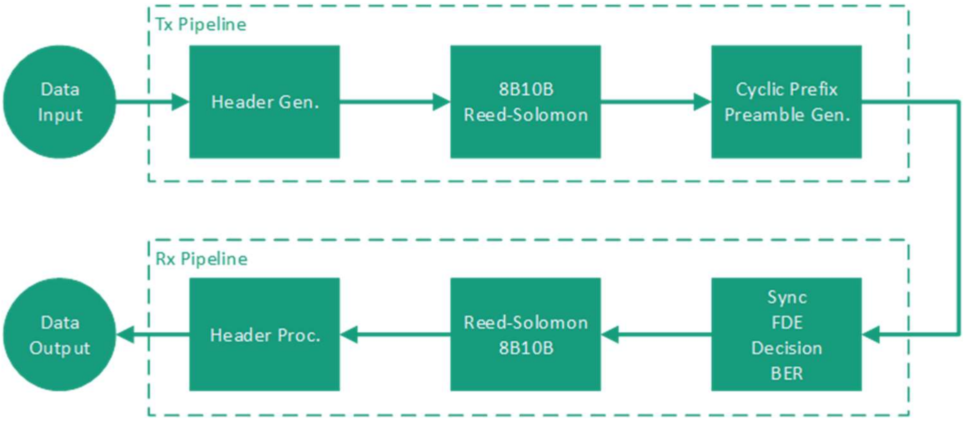

Figure 50: OOK PHY implementation based on IEEE P802.15.13

8.3. Documentation

In total 90 function are available for the PHY implementations with each consisting of:

- Detailed input and output parameter descriptions
- References to the related publications and standards
- Input parameter checks and detailed error descriptions
- Test environments

The documentation is based on Doxygen (https://www.doxygen.nl/index.html) and can be called directly within Matlab.

8.4. LiFi channel model

The LiFi channel model offers a number of implementations for various LiFi channels. Main functionalities are:

- Line-of-sight (LOS) channel
- Diffuse channel
- Analog frontend impairments
- Blockages
- Movement
- Various Visualizers
- Pre-configured scenarios: indoor room, industrial scenario (with robot), outdoor scenario

The diffuse channel is based on a frequency domain approach, which drastically reduces the number of necessary calculation compared to standard techniques like ray tracing [14]. Analog frontends impairments include aspects like frequency behavior, e.g. low-pass, clipping effects are additional noise. The wireless channel itself is calculated based on transmitter and receiver positions, including

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the orientation and the field of view (FOV) of the frontends as well as arbitrary blockages as shown in the geometrical model in Figure 51.

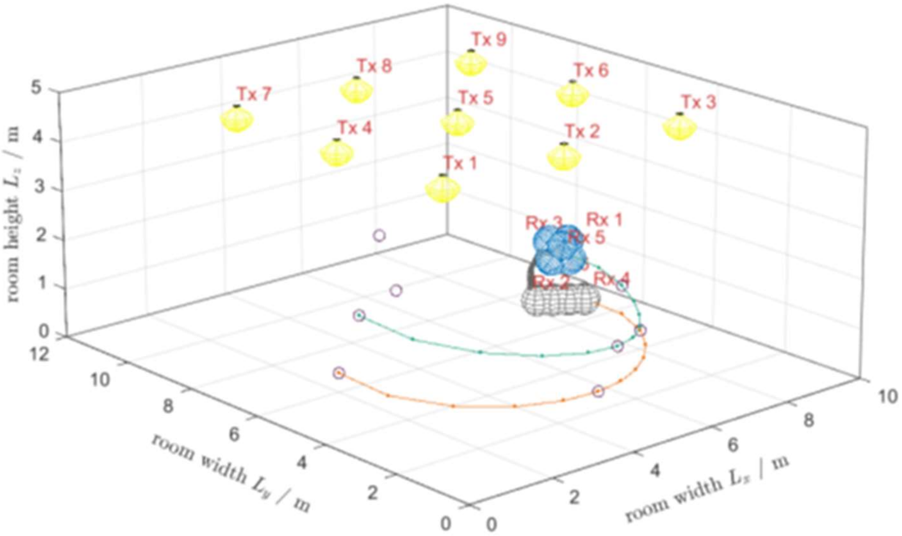

Figure 51: Channel model room geometry visualizer.

The movement feature allow the introduction of movement of the receiver units along a predefined trajectory and the evaluation of the channel that path. The channel model also provides various visualizes as shown in Figure 52 like the frequency response evolution, optical power evolution for each transmitter, the optical power spatial distribution, the geometrical channel model or the radiation and field-of-view characteristics.

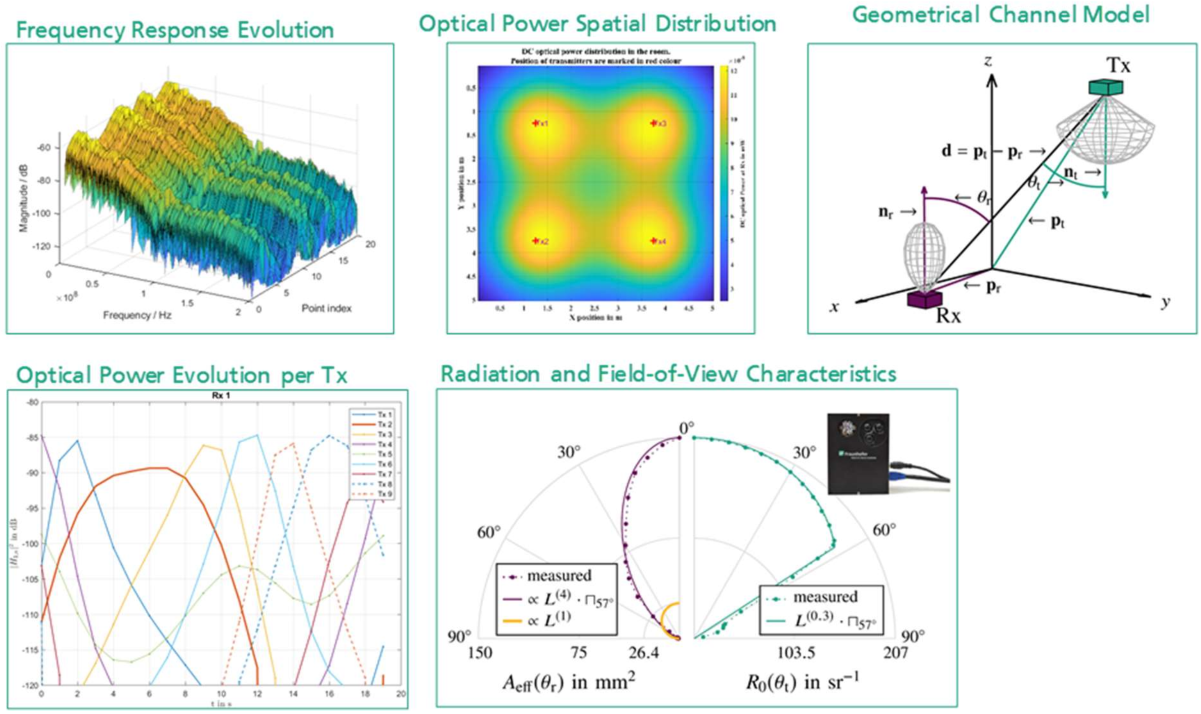

Figure 52: Visualizer and characteristics of the LiFi channel model

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8.4.1. Example of a LiFi channel model

The example below shown the LiFi channel model applied for a moving robot (Tx) inside a LiFi cell (Tx). Starting points are the frontend parameter of Tx /Rx and positions of the robot arm.

main program (main file for the program execution)

createLogicalChannel (bit stream generation)

pulsedTransmitter (modulation)

TxFrontend (filter + clipping)

robotPosition (calculates a trajectory for given robot points in a room)

robotArmPosition (calculates the positon of the robot arm)

createConeFamily (creates signal cones for Tx units (lamps) and Rx unit (robot arm))

geo2ch (generates channels from Tx and Rx cones)

channel (applies channels to signal)

visualization (plots signal and channel properties)

In Figure 53 the interpolated trajectory based on the given position of the robot, the channel behaviour over time for each channel and the channel fluctuation in relation to the noise are shown.

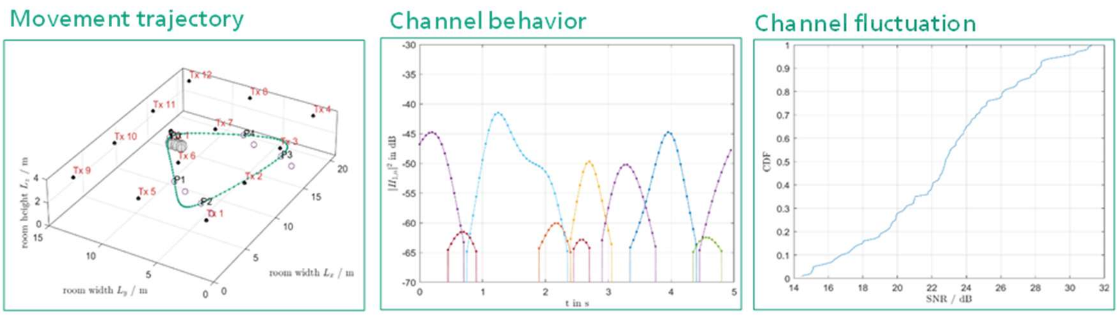

Figure 53: Example of LiFi channel model for moving robot inside a LiFi cell.

8.5. Verification of PHY implementation and channel model

The toolbox functions have been used and have been verified in various publications and in the standardization work in ITU-T and IEEE of HHI inside the ELIoT project. The most important publications with relation to the software library are:

- 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, March 2021, doi: 10.1109/TGCN.2020.3038692.
- M. Hinrichs *et al.*, "Pulsed Modulation PHY for Power Efficient Optical Wireless Communication," *ICC 2019 - 2019 IEEE International Conference on Communications (ICC)*, 2019, pp. 1-7, doi: 10.1109/ICC.2019.8761150.

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- Hinrichs, Malte, et al. "Advanced physical layer design for Li-Fi in the industrial Internet of Things." *Signal Processing in Photonic Communications*. Optical Society of America, 2019.
- Mana, Sreelal Maravanchery, et al. "An Efficient Multi-Link Channel Model for LiFi." *2021 IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. IEEE, 2021.
- H. Schulze, "Frequency-Domain Simulation of the Indoor Wireless Optical Communication Channel," in *IEEE Transactions on Communications*, vol. 64, no. 6, pp. 2551-2562, June 2016, doi: 10.1109/TCOMM.2016.2556684.
- Wilke-Berenguer P - Real-Time Optical Wireless Mobile Communication With High Physical Layer Reliability [JLT 2019]

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9. Conclusion and outlook

This specification specifies a LiFi open reference architecture to facilitate harmonized implementations of various use cases to demonstrate the potentials and unique features of light communications for the Internet of Things. The open reference architecture enables synergies in the deployment of LiFi through the definition of common interfaces for system integration. Example use cases and the derivation of a common architecture of the LiFi interface builds the base for the definition of open interfaces for the data path as well as the control of the LiFi interface circuitry. Various extensions to the open reference architecture are proposed to accommodate enhanced functional requirements, like the separation and spatial distribution of the optical front end from the modem part through fronthaul links, or enhancements in throughput as well as coverage through the deployment of MIMO technologies.

The document also shows that the proposed open reference architecture is aligned with all existing LiFi standardization and can progress the technology towards unified interfaces regardless of the standards or design principles used for implementation. Through investigation of integration with common network architectures as specified through IEEE 802.1CF and 3GPP TS 23.501 the usability of the open reference architecture for real networks was verified.

The LiFi Open Reference Architecture is accommodated by the LiFi reference software library, which has the objective to provide a toolbox for evaluation of new functions for the support of mobile IoT devices including means for optimization and verification of results. The software library consists of multiple @Matlab based functions which can be used for applications like LiFi system performance analysis, network planning, modelling of LiFi channel impairments, and various aspects of testing.

An area of improvement could be the architectural support of QoS, high reliability, and time-bounded communications over LiFi. The abundance of the transmission resources of the light medium and the easy manageability of exclusive access could allow for the same QoS capabilities as available in 5G cellular communications. So far, no work has been done for non-cellular technologies to provide architectural prerequisites to enable matching capabilities and management models.

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References

[1] K. L. Bober and et al, "A Flexible System Concept for LiFi in the Internet of Things," in *ICTON 2020*, 2020.

[2] M. Müller, P. Behnke, P.-B. Bök and K. L. Bober, "Leverage LiFi in Smart Manufacturing," in *2020 IEEE Globecom Workshops*, Taipei, Taiwan, 2020.

[3] T. Metin, M. Emmelmann, M. Corici, V. Jungnickel, C. Kottke and M. Müller, "Integration of Optical Wireless Communication with 5G Systems," in *2020 IEEE Globecom Workshops*, Taipei, Taiwan, 2020.

[4] ISO/IEC 7498-1, Information technology — Open Systems Interconnection — Basic Reference Model: The Basic Model, 1994.

[5] IEEE Std 802.11-2020, IEEE 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, 2020.

[6] IEEE P802.15.13, Draft Std. for Multi-Gigabit per Second Optical Wireless Communications (OWC) with Ranges up to 200 meters, https://standards.ieee.org/ieee/802.15.13/10269.

[7] ITU-T G.9991, Access networks – In premises networks: High-speed indoor visible light communication transceiver – System architecture, physical layer and data link layer spec, https://www.itu.int/rec/T-REC-G.9991, 2021.

[8] "nl80211," [Online]. Available: http://git.kernel.org/cgit/linux/kernel/git/linville/wireless.git/tree/include/uapi/linux/nl80211.h?id=HEAD.

[9] IEEE Std 802.1CF-2019, IEEE Recommended Practice for Network Reference Model and Functional Description of IEEE 802 Access Network.

[10] IEEE Std 802-2014, IEEE Standard for Local and Metropolitan Area Networks—Overview and Architecture..

[11] *IEEE Std 802.1Q-2018, IEEE Standard for Local and Metropolitan Area Network- Bridges and Bridged Networks.*

[12] 3GPP TS 23.501 V16.6.0 Release 16 (2020-10), System Architecture for the 5G System.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 825651 (ELIOT)

[13] ITU-T G.9960, Access Networks - In premises networks: Unified high-speed wire-line based home networking transceivers - System architecture and physical layer specification, https://www.itu.int/rec/T-REC-G.9960, 2022.

[14] H. Schulze, "Frequency-Domain Simulation of the Indoor Wireless Optical Communication Channel," *IEEE Transactions on Communications,* vol. 64, no. 6, pp. 2551-2562, June 2016.

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