Enhance Lighting for the Internet of Things

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Introduction

This document presents the public results from WP3 “Concepts and Algorithms” of the ELIoT project. In order to reach as large an audience as possible, D3.6 was prepared and submitted in the form of a paper for the European Conference on Networks and Communications (Porto, June 2021).

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ELIoT: New Features in LiFi for Next-Generation IoT

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***Abstract*—The Internet of Things currently is predominantly narrowband and cannot always guarantee high reliability and low latency. Future IoT applications such as flexible manufacturing, augmented reality and self-driving vehicles need sophisticated real-time processing units in the cloud to which mobile IoT devices are connected. These high-capacity links meet the requirements of the upcoming 6G systems and cannot be facilitated by the current mobile communication infrastructure. Light communication, which is also denoted as LiFi, offers huge amounts of spectrum, extra security and interference-free transmission. We present the current state-of-the-art of LiFi systems and introduce new features needed for future IoT applications. We propose a distributed Multiple-Input Multiple-Output topology with a fronthaul using a plastic optical fiber. Such a system offers seamless mobility between the light access points and also to 5G, besides low latency and integrated positioning. Future LiFi development, implementation and efforts towards standardization are addressed in the EU ELIoT project which is presented here.**

Keywords*— Future IoT, LiFi, Optical Wireless Communication, Light Communication, IEEE 802.11bb, ITU-T G.vlc

I. Introduction

As the amount of wireless data traffic keeps growing at exponential rates, the pressure on radio spectrum increases. Over the past decades, we have seen waves of innovation to enhance the bit rates (bit/s) and the density (bit/s/m^2) that can be provided by wireless radio networks, but the wireless technology needed to support this also becomes increasingly complex. For instance, massive multiple-input and multiple-output (MIMO) and beam steering in 5G push the radio technology limits but the complexity likewise. One can argue that a disruptive change to include optical wireless communications, which is also denoted as LiFi, becomes attractive. For lightwaves, walls, celing and floor are natural boundaries between the wireless cells that allow very dense reuse of a vast amount of optical spectrum. Light sources such as light emitting diodes (LEDs) can offer gigabits per second with simple emitters and receivers at very low cost.

Communication via light conceptually is older than radio, but when local area networking (LAN) went wireless in the 1990's, the demand for coverage across multiple rooms was larger than the desire to very densely reuse the spectrum among the, at that time, rather few users. Meanwhile, since the 1990s, WiFi and cellular technologies became ubiquitous. The majority of the increased capacity is due to cell sizes which have shrunken steadily as the need to serve many more users in dense areas grew. Extrapolating these trends explains the increasing interest in LiFi, which can cover small "personal" cells with very high data rates.

Particularly, the Internet of Things (IoT) can be seen as a driving force behind further densification. The IoT is often characterized as a vast multitude of many devices that each generate only limited traffic, but collectively cause a substantial increase in traffic. In the future IoT, we can see numerous applications in factories in which machines, industrial devices and smart glasses demand higher rates and lower latency, besides increased link reliability [1, 2]. LiFi has a high potential to address these future needs.

Fig. 1: IoT use cases targeted by the ELIoT project.

While first LiFi systems are rolled out commercially, it is clear that further innovation and new features are needed to exploit its full potential in several applications, as shown in Fig. 1.

This paper describes how these challenges are addressed in the EU H2020 project ELIoT (Enhance Lighting for the Internet of Things). In particular, the main contributions are:

- Providing interworking with other systems like radio and wired infrastructure
- Realizing mobility horizontally (to LiFi access points) and vertically (to other technologies like WiFi and 5G) and ensure robustness to blockage of a light beam
- Developing cost-effective and easy-to-install in-building backbone infrastructure networks
- Demonstrating end-to-end link security

II. LiFi Concept

There are many interesting applications for the use of LiFi in different environments, such as office, industrial, in-home or outdoor [3]. Each of these poses different requirements, so a single system concept may not be optimal. However, low-cost requirements dictate that solutions for the various use cases can be compiled from flexible functional components, exploiting commonalities and reusability of hardware and software [3]. In fact, network integration of LiFi as a layer 2 LAN, equivalent to a classical Ethernet connection, is needed and provides good versatility by supporting various protocols like the internet protocol (IP) or industrial automation protocols like Profinet, see Fig. 2. Common physical layer (PHY) convergence formats are important for harmonization. These constitute the key commonality of solutions together with common MAC frame formats.

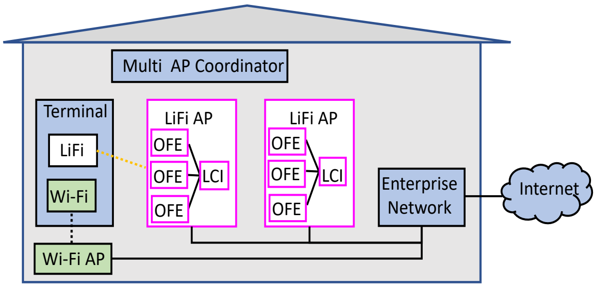

Fig. 2: Indoor system architecture overview comprising LiFi and WiFi access technologies.

Compatibility at the PHY is possible by selecting a common mandatory transmission mode, used for network access and spectrum coordination. The most widely used LiFi PHY makes use of direct current (DC)-biased orthogonal frequency-division multiplexing (OFDM) with adaptive bitloading to allow scalability and exploit the full capacity of LiFi. Distributed MIMO (D-MIMO) is optional and supports spatial multiplexing and diversity, based on subcarrier-wise channel estimation, feedback of the channel state information, joint precoding to select a scalable subset of adjacent optical front ends (OFEs) and equalization at the mobile device. D-MIMO can avoid frequent handovers associated with the small optical cell size, thus ensure consistent quality of service (QoS) and reliability for high mobility and high user densities. To support battery-constrained devices, a low power PHY can be very useful in the uplink, e.g. based on on-off keying with frequency-domain equalization [4]. It would be natural to use this low complexity PHY also as the common mode. For integrated positioning, the PHY performs sub-sample accurate timing measurements based on a conventional ranging (also denoted as timing advance) aided by additional phase estimation in the frequency domain. If this approach is combined with distributed MIMO, the MAC can triangulate the position of the terminal and reach centimeter precision.

For QoS, the channel access mechanism supports reservation-based time-and-space-division multiple access (TSDMA) for traffic flows with guaranteed throughput and latency. Power saving through scheduled sleep periods supports longer battery lifetimes. The backhaul connects the LiFi infrastructure to a fixed access network with a common interface to the higher layer services. This backhaul network may be realized over different media, for example: Ethernet, power line communications (PLC) and plastic optical fibers (POF) each having its own capacity and latency characteristics. A unified interface for the backbone network allows versatile integration. To integrate LiFi and Wi-Fi, access points (APs) and devices provide interfaces to the IEEE 1905.1 standard which represents both technologies as one link towards the network layer. The identified main functional components of LiFi connectivity can be combined in order to build practical solutions for different use cases. Extended functionality for specific solutions can be realized through software modules. Functions comprise link monitoring, remote configuration based on standard protocols, as well as QoS management and service metering.

III. Mobility Support

The ELIoT project works towards the migration of LiFi into 5G by using a common infrastructure that brings redundancy into the radio access network (RAN). With the emerging 5G systems, cloud access infrastructures will play an important role in both, uplink and downlink operations. ELIoT studied mobile registration and the handover mechanism, see Table 1. Network function virtualization (NFV) and software defined networking (SDN) are main tools on both, control and user planes. For this purpose, technical specifications for 3GPP and non-3GPP access types are available in the standards. We aim at a compatible solution which covers vertical handover functionality between LiFi and 5G as well.

Fig. 3. shows a top-down overview of the integrated 5G security system. On the one hand, unlicensed non-3GPP access over LiFi, while, on the other hand, 3GPP access procedures take place based on the existing specifications. In the right side of Fig. 3, the Open5GCore [5] platform is deployed on server or container systems, allowing the official test procedures. In order to secure communication over unlicensed access technologies, an enhanced tunneling algorithm for IPsec and the security association protocol EAP have been implemented to provide appropriately encrypted and encapsulated message transactions.

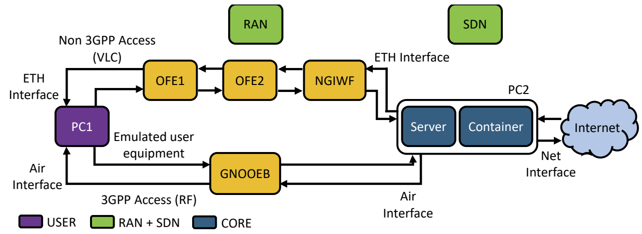

Fig. 3: LiFi-5G system integration.

Seamless large-area coverage involving multiple LiFi APs will be provided in ELIoT. Management and service of the LiFi network needs to be fully integrated with the corporate IT. We distinguish between various mobility scenarios.

Table 1: Handover mechanism between LiFi and WiFi and between LiFi APs

Term	Description / definition
Vertical L3 handover	moves IP-level connectivity of a terminal between different access technologies and a LiFi network. The terminal's IP address might be preserved.
Vertical L2 handover	moves layer 2 connectivity between a Wi-Fi network and a LiFi network. The terminal's MAC address is preserved.
Horizontal handover	transfers of association state between two neighboring, possibly coordinated, APs. This is independent of the interference coordination between the APs.
MIMO link adaptation	a single AP optimizes the use of multiple OFEs to aid a terminal's mobility. Association remains in the AP.

a) Moving within coverage area of a single AP

In this scenario, multiple OFEs provide LiFi access in a service area (e.g. a single room) via a common AP. Through other OFEs, the LiFi-AP keeps the connection alive even if the line-of-sight towards one OFE is accidentally blocked. Moreover, if the terminal is moved or rotated, the connection is maintained. The

LiFi-AP and terminal may optimize link performance by taking advantage of the light traveling via different signal paths. This is realized by using the D-MIMO technology. 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 subset of OFEs for this terminal and by adapting the physical layer parameters (e.g. bit loading) for optimal link quality. The LiFi-AP can trade-off between robustness and power consumption. For robustness, the AP may activate all its OFEs for a terminal. To reduce power consumption, the AP may activate only the best OFE.

b) Moving between APs with isolated coverage areas

In this scenario, multiple areas are each served by a LiFi-AP, whereby these areas are optically separated. This is typically the case for the situation of multiple (small) rooms in a building. No interference occurs between APs. If a terminal moves from one area to another, it typically enters an intermediate area (e.g. a corridor) without LiFi coverage and loses LiFi connectivity temporarily. As soon as the terminal re-enters an area with LiFi coverage, it re-connects (rapidly) to LiFi.

c) Moving between APs with overlapping coverage areas

In this scenario, a (large) area (e.g. an open office space) is served by multiple LiFi-APs, each covering part of the total area. Now the coverage of APs intentionally overlaps to prevent dead zones. A terminal in an overlap area connects to one AP while interference has to be managed, e.g. by coordinating APs. Motion of terminal across service areas is similar to Wi-Fi: a terminal can initiate a handover. This could be a “break before make” handover, whereby the LiFi link is lost, but most preferably a “make before break” handover is supported to keep breaks of the LiFi link short.

LiFi will have much smaller cells than Wi-Fi and more abrupt cell fringes. This demands a fast handover. A terminal therefore preferably anticipates a handover by pre-registering to a neighbouring AP and pre-establishing security keys via the currently active connection and the backhaul. The line-of-sight propagation characteristics of LiFi requires adequate handling of interference and hidden-terminal problems. A terminal typically sees the APs, but not to any of the other terminals. An AP sees terminals but not the neighbouring APs. Hence, carrier-sense multiple access (CSMA) may not prevent APs (or terminals) from transmitting at the same time. LiFi preferably uses a coordinate medium access. This also strengthens the ability to guarantee QoS, by organizing the medium access so that that the link it is not hampered by interference.

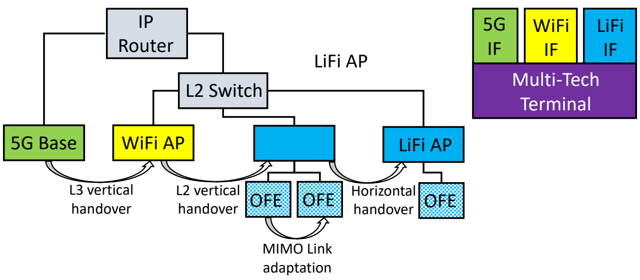

Fig. 4: Terminal moving out of LiFi coverage area, remaining in Wi-Fi coverage area (different APs).

d) Moving in/out of LiFi area within a Wi-Fi area

In this scenario, a small area is served by LiFi (e.g. a single room), while a larger area is covered via Wi-Fi (e.g. multiple rooms). For a terminal that moves in or out of the LiFi area, a vertical L2 handover between LiFi and Wi-Fi takes place. A terminal in the LiFi area can off-load the traffic from Wi-Fi and increases its QoS. A terminal that moves out of the LiFi area keeps a connection through Wi-Fi, as shown in Fig. 4. Ideally, by aggregating two wireless techniques, their throughout is added. In IEEE Std. 802.11, L2 handover is defined by fast BSS transition and fast session transfer. As LiFi is not yet tightly integrated into 802.11, alternatively, integration of both techniques can be realized via the IEEE Std. 1905.1. Note that the WiFi mesh technology reuses clauses from the same standard. ELioT addressed innovations in [6].

e) Interference Management

Contiguous coverage mostly implies that cells will overlap and interfere mutually. A distinction from RF is that as LiFi nodes communicate via a directional line-of-sight (LOS), which keeps the interference strictly localized to the overlap of the adjacent illuminated areas. There is no leakage into remote cells, due to rich multipath propagation, like in indoor radio systems. Our reference system contains ceiling-mounted LiFi APs while LiFi Terminals (EP) are spread in the area. Fig. 5(a) depicts the coverage areas of AP1 and AP2 in solid grey and those of the EP1 and EP2 in dashed line, respectively. The red arrow in Fig. 5(a) shows how AP1 interferes with AP2 transmitting to EP2 (white arrow down). AP2 may not detect transmissions from AP1. Fig. 5(a) also shows that EP2 is a hidden node for EP1. LOS propagation limits the coverage to a specific cell, such as a specific machine. This makes it possible to reuse the optical spectrums quite frequently, so that high data rates become available at each machine individually in the factory hall.

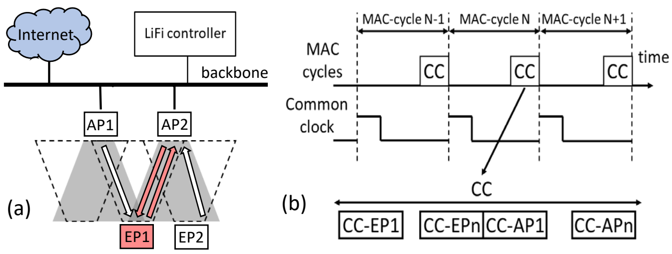

Fig. 5: LiFi network consisting of fixed APs and mobile user terminals EPs (a) and MAC cycle alignment to common clock and CC (b).

To avoid that the interference can significantly degrade the performance, we can divide the channel resources over the contending nodes, which is possible by time division, modulation-frequency division, code division or wavelength division. These techniques come with a flexible MAC protocol that can handle contention, where CSMA or TDMA are preferred. In CSMA, a node “listens before it talks” while in TDMA a node adheres to a coordinated scheduling scheme. CSMA can flexibly handle random arrivals but may not guarantee access for ongoing sessions. For OWC, CSMA has the drawback that APs and EPs are not guaranteed to see each other. This favors TDMA, whereby the network of APs determines the scheduling on the medium. Contentions are resolved by coordinating the time-schedules among adjacent APs. In the ITU-T G.9991 recommendation, TDMA has been adopted. The protocols can run as a specific firmware on ICs available for ITU-T G.9960/G.9961. ITU-T G.9961 separates the network into “domains”. For powerline communication, interference between multiple domains is mitigated by mechanisms that are suitable for LiFi, too. In fact, a LiFi domain is seen as a part of a larger LiFi network. The domain concept may also fit to IEEE Std. 802.11, if a LiFi domain is regarded as a basic service set (BSS). Inter-domain interference is handled in ITU PLC by a distributed protocol. Management messages have to be transferred over the same powerline as the data, which is a shared medium. For OWC, we propose to exploit the opportunity of connecting every domain via their AP to a backbone which exchanges inter-domain management messages via unique connections. Fig. 5(b) shows this architecture, which handles inter-domain interference faster and more efficiently. A dedicated LiFi controller (LC) handles and manages inter-domain contention, but does not act as a traffic router in the backbone. The LC observes instances of inter-domain interference and coordinates APs by setting constraints to their access schedules which avoid possible collisions. The LC can be implemented as a central entity, but its functionality may also be distributed among the APs while the APs can nonetheless converge to a common, mutually coordinated scheduling. A common clock is shared among the domains to coordinate the MAC-cycles in multiple domains. Fig. 5b shows how APs are synchronized, it can be realized by running the precision time p rotocol (PTP) according to IEEE 1588 over the backbone. APs and EP terminals advertise their presence over a common channel (CC) to detect potential inter-domain interference. Every AP tracks the activity of neighboring nodes. It reports interference events to the LC, to allow it to set scheduling constraints for adjacent APs to resolve conflicts. We illustrate this for the scenario in Fig. 5. In domain 1, EP1 receives advertisements of AP2 belonging to domain 2. AP1 informs the this as an interference risk to the LC. In response, the LC constraints AP1 by only allowing transmission to EP1 in a limited set of timeslots. It also constraints AP2 by prohibiting this set of slots in any communication with its own EPs. The algorithm to set time-division constraints is left as an opportunity for proprietary innovation, as it does not need to be fixed in ITU-T G.9991. A certification authority may be needed to ensure interoperability of LCs, APs, and EPs from different vendors.

IV. BROADBAND PHY COMMUNICATION

POFs can be attractive for the analog fronthaul of LiFi systems due to their do-it-yourself (DIY) deployment capabilities and immunity against electromagnetic interference [7]. To accommodate D-MIMO in the wireless link, two techniques can be used for POF-based LiFi fronthaul: space-division multiplexing (SDM) and wavelength-division multiplexing (WDM). SDM realizes point-to-point connections at the same wavelength over POF to connect each OFE to the AP, as depicted in Fig. 6(a). The main advantage of SDM is that there is no optical crosstalk in the optical feeding network, see Fig. 6(a). For the WDM approach, a common POF is used to distribute the signals to the OFE by using different wavelengths, as illustrated in Fig. 6(b). WDM can simplify the installation and maintenance, however it has higher complexity. With WDM, the amount of crosstalk between MIMO channels can be significant, if there is overlap in the optical spectrum. The crosstalk can be avoided using narrow optical light sources, such as lasers, however a lower cost system can be realized by using LEDs, which have a wider spectrum, thus higher spectral overlap. OFDM with adaptive bit loading can handle the low-pass nature of LEDs. Yet, a new insight in ELIoT is that the color crosstalk in the POF is not necessarily harmful as it can be mitigated by end-to-end MIMO processing applied anyhow for the wireless link.

To satisfy the non-negativity in intensity-modulated/direct-detection (IM/DD), a constant DC bias is added to the waveform. A real-valued waveform is reached by applying a frequency-upshift to the complex-valued baseband signal to an intermediate frequency with is slightly higher than one half of the signal bandwidth. To avoid clipping noise and distortion [8], the modulation power is limited. We describe the end-to-end channel from N_T emitters to N_R receivers by a N_R x N_T MIMO matrix $(f) = \boldsymbol{Z}(f)\boldsymbol{G}(f)$. That is, it is the product of the crosstalk coefficients from the POF fronthaul link represented by $\boldsymbol{G}(f)$ and the coefficients of the spatial overlap in the wireless channel given by $\boldsymbol{Z}(f)$. To evaluate the throughput of the DCO-OFDM MIMO link, a singular value decomposition (SVD) of the overall channel matrix $\boldsymbol{H}(f)$ is computed and the overall throughput is estimated by [9]:

$$R = \Delta_B \sum_{n=1}^{N}\sum_{k=1}^{K} \log_2\left(1+\frac{SNR}{N_T\eta_H\Gamma}\xi_k^2(f_n)\right) \qquad (1)$$

where Δ_B is the bandwidth occupied by each subcarrier, N the number of subcarriers, K the rank of $\boldsymbol{H}(f)$, SNR is the transmitted signal-to-noise ratio, η_H the average path loss, $\Gamma = 10$ reflects typical system properties and DC biasing [7, 10, 11] and $\boldsymbol{\xi}_k(f_n)$ is the k-th singular value of $\boldsymbol{H}(f)$ at the n-th subcarrier. We found that the property that $\boldsymbol{Z}(f) = \boldsymbol{Z}_0$ is mostly constant over frequency and that the response of $\boldsymbol{G}(f)$ mainly stems from known component properties, which allow efficient implementation and limit protocol overhead.

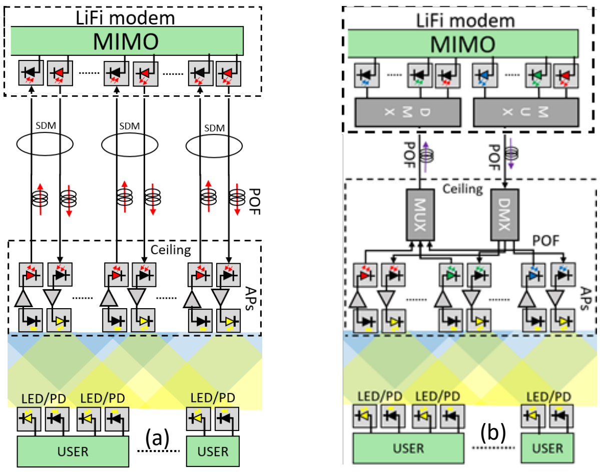

Fig. 6: (a) SDM and (b) WDM approach in the fronthaul over POF

We have realized measurements for the SDM-over-POF with D-MIMO considering the channel response for the whole system. For our specific purpose we only had access to commercially available red LEDs , so we characterized the WDM-over-POF using two laser diodes (LDs) at 520 nm (green) and 658 nm (red). The WDM-over-POF link is characterized by measuring the losses due to light absorption in the plastic fibre and the crosstalk in the wavelength domain. The losses for the green and red channel are asymmetrical due to differences in emitting and received optical power and due to different receiver sensitivities for either wavelength. Considering only the optical link for WDM, a throughput of 2.5 Gbps is achieved for the green wavelength channel and 4.3 Gbps for red. To evaluate the performance of WDM-over-POF with D-MIMO, the POF link and the wireless link channel response are measured separately and then concatenated. The experimental setup is presented in Fig. 7, where d_1 is the distance between OFEs and user receiver, d_2 distance between receivers and d_3 distance between the APs. Two measurement scenarios are implemented to exemplify the downlink of a high bandwidth multi-user MIMO transmission for LiFi. In the first scenario, the access points and users located at $d_1 = 100$ cm, $d_2 = 70$ cm and $d_3 = 70$ cm. In the second scenario the receivers are placed closer at $d_1 = 50$ cm, $d_2 = 50$ cm and $d_3 = 35$ cm. From the singular values of $\boldsymbol{H}(f)$ and considering an SNR of 20 dB, the achievable throughput of the system is calculated using (1). Table 2 reveals that the performance for SDM is slightly better compared to WDM. In SDM, the POF channels are spatially separated using independent fibre links. The absence of spectral overlap between channels increases the bit rate. The WDM system lacks excess margins to become insensitive to unequal link budgets which worsens after crosstalk removal due to anisotropic noise enhancement in the MIMO equalizer. In particular, the green channel appears challenging due to lower optical power and lower responsivity at the receiver. In both scenarios, the red channel can carry more data. A power loading technique can be used to allocate more power to the weaker channels and equalize the performance. We observed that the optical WDM link provides high performance, but throughput reduces when the wireless channel is added. Note that the SDM have been done with LEDs. Even then, the end-to-end link is mostly limited by the wireless channel rather than by the POF [7].

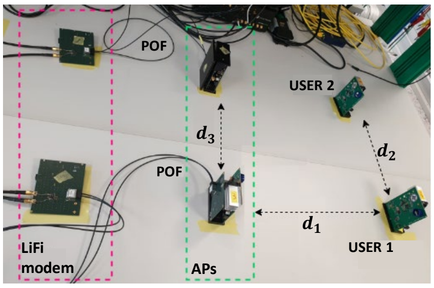

Fig. 7: Experimental setup for D-MIMO over POF using SDM.

Table 2: Throughput evaluation of D-MIMO setup in two different scenarios.

D-MIMO SDM		D-MIMO WDM	
Scenario 1	586 Mbps	Scenario 1	484 Mbps
Scenario 2	421 Mbps	Scenario 2	369 Mbps

V. INDOOR POSITIONING

Communication is the fundamental requirement of smart manufacturing. In addition, LiFi enables indoor positioning. This facilitates various new applications in smart factories. For example, reliable indoor positioning is necessary for using intelligent transport systems (ITS) that transport parts on pallets from predefined locations to other predefined locations. It is usual that transport systems in factories and warehouses travel along predefined paths, defined by inductive loops or optical markers on the floor. But these systems are not flexible, and modifications need effort. LiFi enables localization beyond predefined paths and allows extended positioning use cases due to more degrees of freedom. For example, a transport system can determine a new path on-demand to drive around an obstacle that occurred on the planned path. In addition, there are new opportunities when production resources can be located on-demand. For example, its position can be displayed on a digital factory map. This makes it possible to find a tool, a container with raw material or (semi-) finished products needed in a few seconds, which supports the work of machine operators and production planners. In addition, real-time positioning of mobile devices can 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).

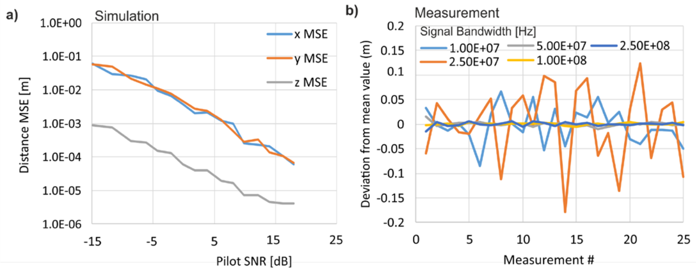

Fig. 8: (a) Calculated distance mean-square error for simulation (100 MHz of bandwidth) and (b) measured distance deviation for multiple signal bandwidths

In the ELIoT project, we propose to realize positioning based on a multi-lateration algorithm, which measures the wireless propagation times between a mobile device and multiple LiFi APs at the ceiling [10, 12]. The ranging or timing advance algorithms behind positioning are well understood and used in fixed and mobile access systems [13]. The accuracy of the result depends primarily on the quality of estimating the time-of-flight. To address the inherent synchronization challenges between mobile and ceiling units, an active ping-pong protocol is used to measure the round-trip time. This allows, in combination with standard techniques for clock offset estimation, an accurate estimation of the time-of-flight. To confirm this concept, a series of simulations and measurements have been carried out in ELIoT. Simulations are based on a scenario model utilizing multiple Tx OFEs and a single Rx OFE, together with a typical OFDM transmission system, based on the ITU-T recommendation G.9991. The simulation results in Fig. 8(a) show only very small distance errors even at low SNR for all axis and the measurement results in Fig. 8(b) demonstrate that accuracies below 1 cm are possible with a signal bandwidth higher than 50 MHz.

Enabling real-time positioning requires the integration into a LiFi chipset. Today's chipsets only partly support the proposed concept. The ELIoT project is working with a chipset from MaxLinear that implements the ITU-T G.9991 recommendation. With this chipset a coarse round-trip time estimation can already be achieved by using the time tagging capabilities. More precise timing information can be extracted from the channel frequency response (CFR) as demonstrated by the ELIoT experiements. For a next generation chipset, new APIs have to be developed in the PHY to provide information on the SNR and CFR to the higher layers.

VI. ROADMAP FOR IMPLEMENTATION

The ITU-T approved the ITU-T G.9991 Recommendation for LiFi in 2020. The DCO-OFDM variant of this Recommendation is the base of most developments in the ELIoT project. The goal of this recommendation was to provide a fast-to-market LiFi system with enough performances to cover the main industrial, enterprise and residential use cases. By reusing the OFDM engine with its adaptive bit loading, already successfully used in other Recommendations (i.e., ITU-T G.hn family, aimed to cover in-home connectivity over coaxial, phone and power lines), the resulting ITU-

T G.9991 document allows to build LiFi systems by reusing existing chipsets. This way, early LiFi products can benefit from high-volume, low-cost integrated solutions while providing a good adaptation to the specificities of the majority of the LiFi use cases. This approach allows to rapidly create an early mass market for LiFi systems with a reasonable investment.

In parallel, the ITU-T Q18/15 group is evolving the Recommendation to cover new scenarios and requirements identified during the first LiFi deployments in industry and further scenarios identified within the ELIoT project that were not contemplated in the first version of the Recommendation. Inter-domain handover and interference management is one example. Once the new concepts are fully understood and standardized, this will lead in the future to a second generation of LiFi chipsets that will incorporate specific hardware macros allowing new applications (e.g., positioning). New evolutions are also expected to address power reduction and a better integration with other technologies to foster the adoption of LiFi technology in mobile devices.

The above-described approach allows LiFi vendors to leverage the broad portfolio of existing ITU-T G.hn compliant chipsets in their early products and facilitate interoperability of early solutions early on. It is expected that the reuse of existing ecosystems will facilitate the adoption of the LiFi technology in the market and lower the barriers to deploy this new technology.

G.hn chipsets allowed commercial release of practical LiFi systems before 2020 and built confidence in the upcoming standard. Signify's 2018 products offered a PHY rate up to 350 Mbps for downlink and 250 Mbps for uplink. Meanwhile higher bit rates have also been tested. The LiFi system is connected to a 1 Gbit/s Ethernet backbone. The baseband processing adheres to ITU-T G.9991. OFDM modulation uses a bandwidth of 50, 100 or 200 MHz with a maximum of 512 subcarriers. Each sub-carrier carries QAM levels with up to 12 bits per symbol, according to an adaptive bit loading scheme. The modem combines the signals and sends the waveforms via analog wiring to up to six ceiling mounted OFE's. Fraunhofer HHI developed an advanced combiner prototype, based on POF which is more robust against electromagnetic interference in industrial scenarios also considered in ELIoT. OFEs generally comprise a LED driver (modulator), an IR-LED for the downlink transmitter and a photodiode with transimpedance amplifier for the uplink receiver. Fraunhofer HHI manufactured OFE prototypes with higher power and improved receiver sensitivity intended for larger coverage areas in industrial scenarios. The signals can be received by Signify's LiFi Access Key, i.e., the user terminal is in the form of detachable mobile USB module or "dongle". Fraunhofer HHI released a USB LiFi prototype (LiFi NEON) to reach 1 Gbit/s in the downlink. This is intended for dense user scenarios, e.g. in conference and classrooms. Moreover, there is an advanced outdoor LiFi prototype manufactured which allows 1 Gbit/s over 100 m for fixed wireless access scenarios investigated in ELIoT. These various products and prototypes show that early LiFi technology is flexible enough to cover a great variety of different use cases.Office use cases demand a moderate, but guaranteed throughput in a wide coverage area. According to feedback from the professional market, fairly uniform coverage with several meters range is considered more important than world-record throughput results in a tiny spot. Reliable, guaranteed low-latency QoS at some 100 Mbit/s/device satisfies the expected user experience. Gigabit performance is of interest in dense scenarios when aggregating the traffic of multiple users inside the coverage area. Up to 16 terminals can be served by the LiFi AP in a managed TDMA scheme, within the coverage zone of six OFEs. OFDM allows reliable detection of signals from multiple OFEs. For the uplink direction an IR LED (940nm) is used what allows full duplex communication in the future. The optical power emitted in up- and downlink are well below the eye safety limit with a 40% margin.

VII. Summary

The ELIoT project addresses LiFi features that enable the next generation of IoT applications. These include a distributed MIMO wireless topology which can be supported by SDM/WDM fronthaul transport of waveforms via a plastic optical fibre. The system realizes seamless handovers between the light access points and also to 5G, besides indoor positioning, thus meeting main requirements of the upcoming 6G systems. LiFi-based indoor positioning showed on average 5 cm accuracy. D-MIMO LiFi has been shown to enhance reliability and deliver throughputs of 600 Mbit/s. Concepts to further increase the performance have been already identified. These features are currently being tested towards use-case demonstrations.

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