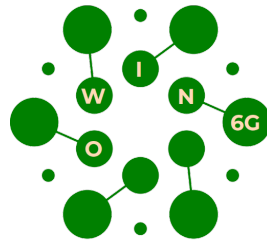


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Project title: Optical and Wireless sensors Networks for 6G scenarios

Work Package 2: Physical and MAC Layer

**Deliverable D2.2 (D7): Final PLC models for preferable
deployment scenarios of future WSNs**

Fraunhofer HHI, Berlin, Germany

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Executive Summary

In this report, the progress of Task 2.2 is presented, summarizing the work carried out on the development of a cascaded PLC–LiFi system as a cost-effective solution for in-home communication.

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1. Work Package Objectives

The work package (WP) objectives are as follow. Highlighted in bolds are the items covered in this report.

Objectives: To

- i. optimize the energy usage of the wireless sensor network (WSN) for Internet of Things (IoT) and Internet of Everything (IoE) applications in sensitive medical and industrial environments, which is crucial for battery-powered sensor nodes (SNs);
- ii. **analyze the limitations of sensor infrastructure, including powerline communication (PLC) as a cost-effective backbone;**
- iii. propose relaying and switching solutions in order to reduce power consumption as well as provide the necessary tools to improve the backbone for radio frequency (RF) and optical wireless communication (OWC) in a WSN;
- iv. provide tools for improving hybrid RF-OWC backbones in WSNs;
- v. design efficient WSN medium access control (MAC) layer protocols that incorporate machine learning and perform a trade-off between data rates and power consumption.

Table I. Summary of T2.2

Work Package Number	WP2	Lead Beneficiary	Farunhofer HHI
Task	2.2		
Start Month	7	End Month	42
WP Name	Physical and MAC Layer		
Task Name	Sensor backbone infrastructure		

Task 2.2: Sensor backbone infrastructure (Leader: Fraunhofer HHI, Conts.: ALL) [DCs 3 and 10]. In this task, we will investigate the limits of sensor infrastructure in the backbone that would facilitate the deployment of WSN in existing buildings. The task includes (i) investigating current limitations and future opportunities of PLC as a low-cost backhaul solution, in addition to optical local area network (LAN)/ fiber-to-the-room (FTTR) systems currently proposed; and (ii) conducting a comprehensive analysis of PLC systems, analyzing their requirements, deployment scenarios, and integration with existing and future RF-optical wireless systems.

A significant progress has been made toward evaluating the feasibility of deploying WSNs in existing building using PLC-based backhaul. A cascaded PLC–LiFi experimental testbed was developed to assess the performance of the system in terms of characterizing the channel behavior, the data throughput with adaptive bit and power-loading schemes, and signal-to-noise ratio (SNR). For this, we first used a light emitting diode (LED) as the transmitter (Tx) followed by a vertical-cavity surface-emitting laser (VCSEL). Using VCSEL with a larger modulation bandwidth we achieved a higher data rate, thereby demonstrating the strong potential of VCSEL in PLC–LiFi networks. In addition, the performance of the LiFi system was further enhanced by using an avalanche photodiode (APD) imaging receiver (Rx). As part of the ongoing work, the latest version of the proposed LiFi system will be assessed using both powerline and fiber backhaul configurations. Furthermore, a multiple input-multiple output (MIMO) technique will be introduced to enhance the system performance by offering a high data rate (in Gbps) link.

2. Motivation

OWC, which is also denoted as light fidelity (LiFi), is emerging as a promising alternative to existing RF-based communication systems. Using the optical spectrum ranging from ultraviolet to infrared (IR) bands offers a number of advantages over RF systems. LiFi has theoretically an unlimited bandwidth using the unlicensed spectrum, thus offering high area capacity and providing inherent security at the physical (PHY) layer [1]. It operates by modulating the intensity of a LED or a laser diode while satisfying eye-safety requirements. Despite its numerous advantages, LiFi still faces a number of research challenges, particularly in establishing an economically viable connection to the router providing wide coverage [1]–[3]. The connection to the network is usually realized via the backhaul, i.e., the LiFi access point (AP) implements the full PHY and MAC layers of the wireless link protocol, which is then integrated through Ethernet over CATx, coaxial cable, plastic optical fibers or PLC protocols. While this is straightforward, it does not address major practical concerns. In particular, regarding the LiFi link, when the line-of-sight (LoS) path is blocked, a handover of the mobile user to another AP is needed, thus increasing the transmission latency and packet losses if implemented at higher layers. A practical approach is to implement the upper part of the LiFi protocol at the central node while deploying the lower layers across multiple distributed optical front-ends (OFEs), with fronthaul connecting the centralized and distributed network functions [4]. To choose the suitable functional split at the fronthaul, different factors such as the use cases, required data rates, and costs should be considered. Ideally, optical fiber is used since it offers much higher data rates, lower losses, and minimum latency [5]. However, costs for fiber deployment can be significant and can vary from country to country [6]. The idea followed in this task is to use the already existing powerlines as a fronthaul for LiFi. PLC is a mature technology based on established standards. Note that, the most recent ITU-T G.9960 standard is also denoted as G.hn [7], which can support point-to-multi-points transmission using a 100 MHz bandwidth and one or two spatial streams. While the standard facilitates transmission of higher than 1 Gbit/s, in indoor environments a typical data rate reached is a few hundred Mbit/s depending on the deployment of the powerline. There is a domain master (DM), which controls time sharing by one or multiple end points (EP) [7]–[9]. LiFi APs can be flexibly deployed wherever powerlines are available, ideally integrated with ceiling-mounted luminaires to provide dense wireless access with low-cost backbone connectivity and no without the need for additional cabling.

The idea to integrate PLC and OWC was originally proposed in [10], where the feasibility of integrating PLC and visible light communications (VLC) was demonstrated both by simulation and experimentally using a commercial PLC modem with a data rate of 100 Kbit/s. As mentioned before, integrated PLC-LiFi systems are especially relevant for indoor environments, offering flexible connectivity, extended coverage, and enhanced throughput [11], [12]. There are two main integration methods, called decode-and-forward (DF) and amplify-and-forward (AF) [13]. DF relay demodulates and re-encodes the signal, offering error correction at the cost of increased complexity and latency [14]. In contrast, AF relay directly forwards the signal, resulting in a simple low-latency design but with inherent noise amplification. The AF method is economically interesting due to its simplicity working like a media converter. Authors in [15] presented a mathematical model of a cascaded PLC-VLC system employing AF relays, demonstrating the interplay between relay gain, end-to-end distance, and system capacity. For instance, the average capacity is 0.04 Bits/s/Hz when the vertical distance from LED to user plane is $L = 3.15$ m and $P_s = 7$ W, and the values of the average capacity are 0.08 Bits/s/Hz when $L = 2.15$ m and 0.12 Bits/s/Hz when $L = 1.15$ m for the same value of the input power. A broadcast system based on AF with two luminaries connected via PLC is presented in [17], achieving 48 Mbit/s using a 8 MHz bandwidth. Our recent work is focused on characterizing the cascaded LiFi over a powerline channel specifically for industrial IoT applications. It provides first practical measurements of the channel and the noise for up to 100 and 300 MHz, respectively [16]. Orthogonal frequency division multiplexing (OFDM) has been a key enabler for high data rates due to its robustness against multi-path fading and ability to optimize spectral efficiency. Simulation results for the bit error rate (BER) of hybrid PLC-4×4 MIMO-VLC narrow-band OFDM transmission over an AF link are presented in [18]. It is shown that with 0.6 m LED spacing the LoS path outperforms LoS+1st reflection by 15 dB SNR at BER 10^{-5} , while reducing spacing to 0.2 m worsens BER by about 20 dB SNR penalty for LOS and 6 dB for L-R1 compared to the first scenario. [19] explored asymmetrically clipped optical OFDM (ACO-OFDM) in a PLC-LiFi link to mitigate impulsive

noise in the PLC channel through the Hermitian symmetry and optimal thresholding techniques. Authors in [20] presented a hybrid cascaded PLC-VLC system using direct current biased optical OFDM (DCO-OFDM) for PLC and code shift keying (CSK) for VLC, analyzing BERs across different noise scenarios. For example, at $\text{BER} \approx 10^{-5}$, the cascaded PLC-VLC link requires $E_b/N_0 \approx 18$ dB under AWGN noise, rising to ≈ 21 dB for impulsive+AWGN noise. While the benefits of OFDM are well recognized, adaptive bit and power loading, commonly used in PLC, remain to be explored in PLC-LiFi systems. In real-world deployments, the cascaded link was reconsidered by combining LiFi front-ends with a commercial devolo PLC modem based on the ITU-T standard G.hn2. It realizes DCO-OFDM with adaptive bit-loading achieving hundreds of Mbit/s in a realistic indoor scenario [21]. These pioneering results stimulate more detailed system-level studies towards a first practical solution in [22]. Finally, a comprehensive survey of the cascaded PLC-LiFi system with a focus on PHY/MAC layer is given in [23].

2.1 Potential Use cases:

Combining LiFi with the existing PLC technology enables seamless extension into the wireless domain with the minimal impact and bridging last-meter gaps between cabled infrastructure and mobile devices. LiFi APs can be flexibly deployed wherever there are powerlines, ideally integrated with ceiling-mounted luminaires to offer dense wireless access with low-cost backbone connectivity and no need for additional cabling.

2.1.1 Residential scenario:

Figure 1 shows a residential scenario with an integrated LiFi over powerline link. LiFi nodes installed on the ceiling are connected via the already existing powerline grid (red cabling) to the Wi-Fi router and therefrom to the Internet. This allows multiple LiFi nodes to be installed per room by simply connecting them to the mains, offering hot spots for robust OWC. Although the basic concept is not new, it avoids new cabling and enables LiFi coverage in large areas at very low costs. Note that installing multiple LiFi nodes within a room helps overcome possible blockages, thereby enhancing both coverage and the overall system reliability. This approach not only reduces installation costs but also mitigates the impact of LoS obstructions by enabling denser node placement. Moreover, as the power grid is deployed in a star topology, from the central fuse box in the home individually into every room, the optical spectrum can be reused in every rooms, thus increasing the overall channel capacity – a characteristic unique to OWC compared with the RF-based wireless systems. Ideal placement of the DM controlling the fixed-wireless medium access of all EPs in one room is therefore nearby the fuse box [26].

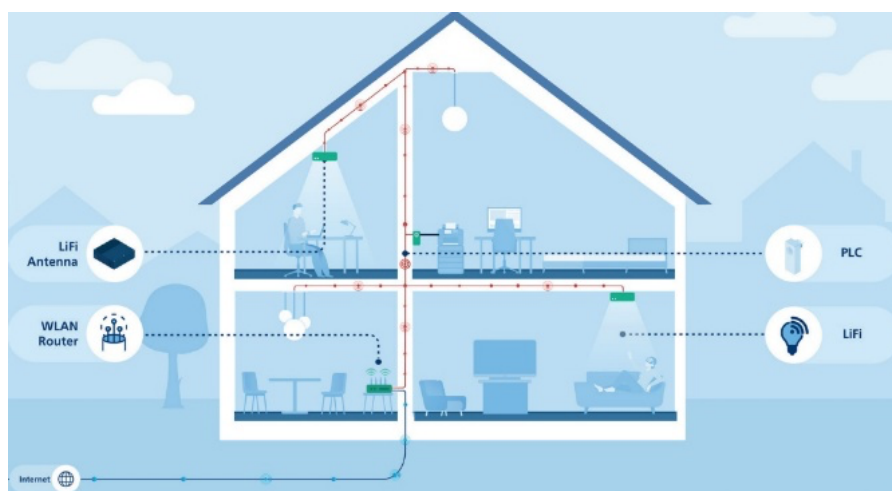


Fig. 1: LiFi over powerline in residential scenario.

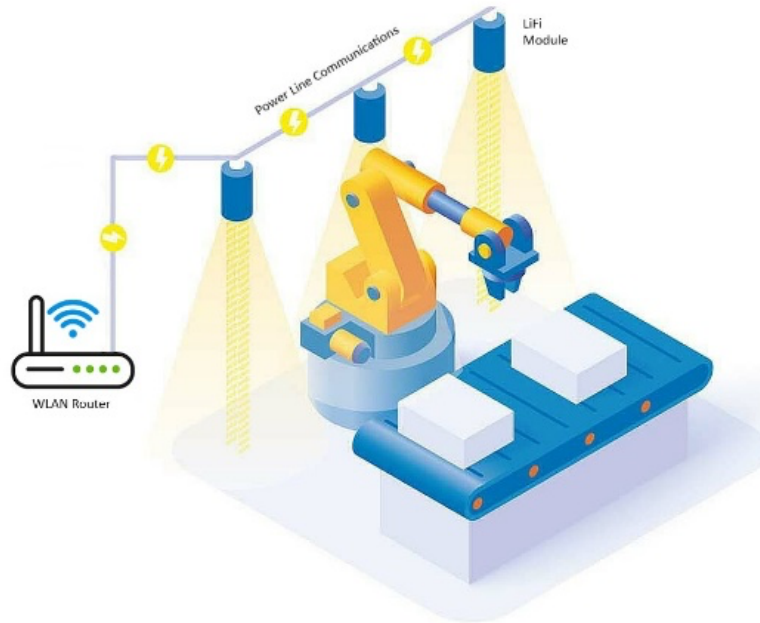


Fig. 2: LiFi over powerline in industrial scenario [16].

2.1.2 Industrial scenario

Another use case is shown in Fig. 2, where the robot arm has a built-in camera for product quality inspection integrated into a LiFi uplink transmitter. The module sends real-time data via LiFi to the powerline network, which then forwards it to the cloud. This setup avoids additional cabling, ensures low latency communication, and simplifies reconfigurations on the shop floor. PLC is used to cost-efficiently connect devices in the IIoT, where RF can not meet requirements such as the reliability and latency. Although optical fiber is ideal for high data rates, its dense installation is costly. This is especially relevant in large manufacturing environments, where frequent changes in machine layout driven by changing production processes necessitate repeated backbone re-installations. Ethernet cabling is also costly to deploy and lacks flexibility in dynamic industrial environments [16].

3. Challenges and Requirements

Although PLC technology is cost-effective and easy to use, some challenges including low data rate and frequent disconnections still remain. To meet evolving service requirements, the following aspects must be addressed.

1. Throughput Improvement

Several approaches can be considered to increase throughput:

- **Extending the frequency band:**

Expanding the bandplan up to 200 MHz or even 300 MHz can significantly increase the data throughput, potentially reaching 2–3 Gbit/s PHY rate over a single-pair power line.

- **Adaptive bit and power loading techniques (e.g., Krongold):**

Powerline channels suffer from multi-path fading and deep frequency notches. Adaptive loading techniques help allocate power and bits more efficiently across subcarriers, thereby improving data rates.

- **MIMO implementation:**

In favorable channel conditions, MIMO can potentially double the achievable data rate.

2. Stability and Reliability Improvement

The following approaches can improve the stability of G.hn-based home networks:

- **Noise filtering:**

Household appliances generate various types of electrical noise that degrade system performance. Installing high-pass filters for noisy appliances can stabilize and lower the noise background. Although this increases deployment cost, it significantly enhances network reliability.

- **Adaptive signal processing techniques (e.g., Fischer–Huber methods):**

These techniques improve robustness against channel impairments and help maintain stable communication performance.

4. Specific Progress

To achieve the objectives outlined in Task 2.2, several investigations were conducted, as outlined below.

4.1 Characterization of LiFi-over-Powerline Channels

The results have been published as [P1] in the 21st International IEEE Conference on Factory Communication Systems (WFCS 2025).

4.1.1 Objective:

- Systematic frequency response measurements up to 100 MHz of the cascaded PLC-LiFi channel using both ideal and an exemplary deployed powerline cable, which yield practical insights into the principal channel properties and will aid in future system deployment and optimization.
- Provide fundamental understanding of how the PLC and LiFi channels contribute in physical layer to typical impairments like signal attenuation, multi-path, interference and noise in a cascaded AF link.

4.1.2 Experimental setup:

Figure 3(a) shows the measurement setup. It consists of a vector network analyzer (VNA, Keysight P5003A), two devolo PLC couplers placed in a safety box (Fig. 3(b)), a power cable, two OFEs mounted on tripods, and a laptop for data logging. A continuous wave (CW) signal with a constant power level of 0 dBm is first transmitted via port A of VNA. VNA measures the frequency response of the device under test (DUT), which are the PLC, LiFi link, and cascaded PLC-LiFi links that are used in this study. Since the PLC link operates at 230 V AC, the system is enclosed in a safety box as shown in Fig. 3(b) that automatically disconnects the power supply if the box door is opened. Within the box, there are two PLC couplers connected to 230 V. The PLC coupler is a proprietary device by devolo, which combines and splits high-frequency and 230 V AC signals in transmit and receive directions, respectively. The signal is transmitted from port A of the VNA to the first PLC coupler through SMA cable. It then passes through the power cable and reaches the second PLC coupler which acts as a high-pass filter, removing the 50 Hz AC component. This filtered signal is then routed to the optical Tx via a SMA cable. The signal is consecutively transmitted over the LiFi channel and received by the OFE Rx, which emulates

a mobile device and is finally connected to port B of the VNA. The VNA records amplitude versus frequency, enabling end-to-end channel analysis.

LiFi Generation-1:

Each OFE uses four high-power 850 nm LEDs (SFH 4715AS) with a common driver for transmitting a wide beam along the same path. Five optical Rx's composed of silicon photodiodes (PDs) (Hamamatsu S6968) individual bootstrap and transimpedance amplifiers (TIA) are used to detect the incoming light signals. To enable transmission over several meters both the transmit power and Rx's with a higher sensitivity can be used. Note that these OFEs were especially developed so that the typical 5-6 m link distances in industrial scenarios can be covered at a data rate of 100 Mbit/s [24], [25].

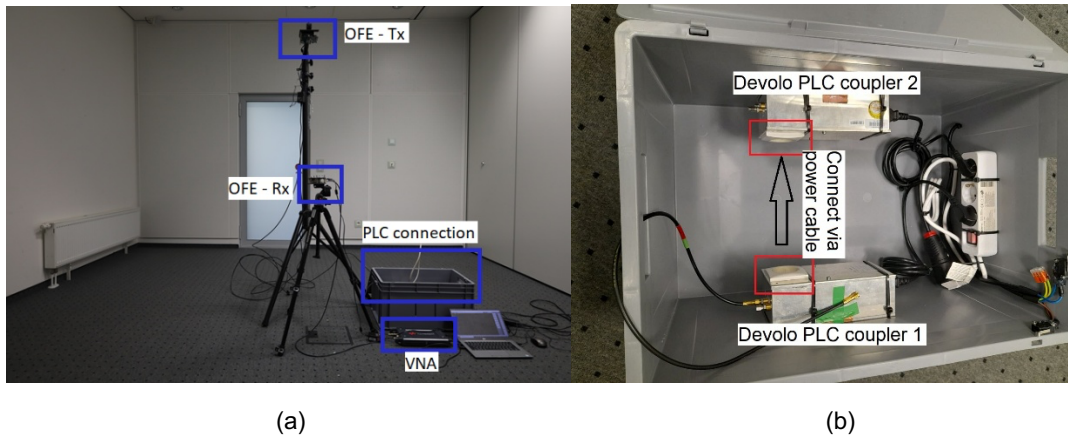


Fig. 3: (a) Experimental integrated PLC-LiFi setup, and (b) PLC connection safety box [16].

4.1.3 Results:

A. Cascaded PLC-LiFi channel:

As it is shown in Fig. 3(a), for a LoS LiFi link both OFEs are in the center of the room facing each other. To investigate the impact of PLC and LiFi components on the cascaded channel measurements are carried out over 1, 5 and 10 m NYM-J PLC cables and 100, 150, and 200 cm LiFi links. Figure 4 illustrates the frequency response of a single 100 cm LoS LiFi link, a single 10 m NYM-J PLC link, and a cascaded PLC-LiFi link over a 10 m long PLC and a 100 cm long LoS LiFi link. This figure is not normalized to show clearly the attenuation in each link. It can be observed in Fig. 4 that a 3 dB bandwidth for the LiFi link is about 93 MHz, while it is reduced to 33 MHz for the cascaded PLC-LiFi link. Up to 50 MHz, the average attenuation is around -1.6, -12.7, and -18.2 dB for PLC, LiFi and PLC-LiFi links, respectively. At 100 MHz, attenuation increases to around -2.7, -13.1, and -27.7 dB for PLC, LiFi and cascaded PLC-LiFi links, respectively. In Fig. 5 (top), the effect of different LiFi link lengths on the amplitude response is illustrated for a power cable length fixed to 10 m. At 80 MHz, the normalized attenuation values for LiFi links of 100, 150, and 200 cm are about -16.8, -23, and -28.5 dB, respectively. Figure 5 (bottom) shows the normalized amplitude response of a PLCLiFi link for different PLC link length, while the length of the LiFi link is kept fixed. At 80 MHz, the attenuation values for PLC link lengths of 1, 5, and 10 m are approximately -14.1, -15.4, and -16.8 dB, respectively. The LiFi link characteristics are determined by the OFEs, resulting in a nearly constant loss, while the PLC link characteristics show increasing loss at higher frequencies. Both are dependent on the

distance. In comparison, when the distance d between the optical Tx and Rx is doubled from 100 to 200 cm, attenuation increases by around 12 dB at 80 MHz, which is explained due to the path loss model for LiFi. Conversely, doubling the power cable length from 5 to 10 m results only in a 1.4 dB increase in the attenuation at the same frequency. Obviously, in a cascaded PLC-LiFi link, the link length of the LiFi link has much more impact than a change in the PLC link length.

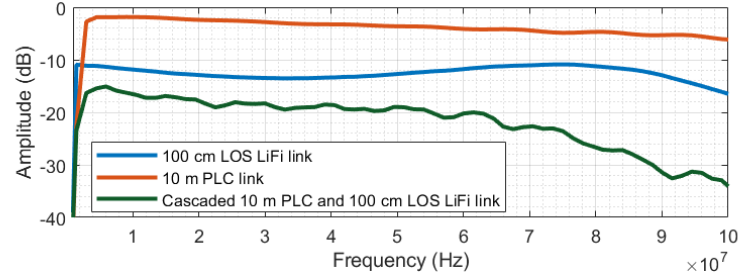


Fig. 4: Frequency response of a single 100 cm LoS LiFi link, a single 10 m PLC link and a cascaded 10 m NYM-J PLC and 100 cm LoS LiFi link (without reference link normalization) [16].

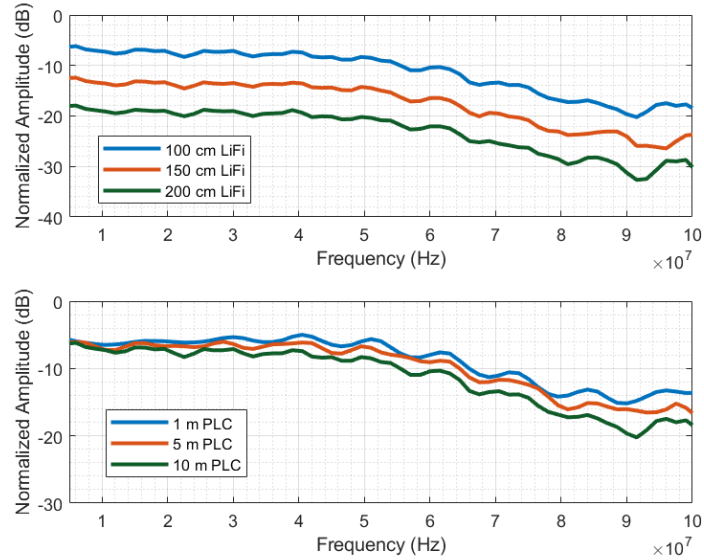


Fig. 5: (top) Normalized frequency response of a PLC-LiFi link with a fixed 10 m PLC link and varying LoS LiFi links. (bottom) Normalized frequency response of a PLC-LiFi link with varying PLC cable lengths and a fixed 100 cm LoS LiFi link [16].

B. PLC-LiFi channel in a real power grid

A powerline cable installed inside the wall in the same room is included exemplarily into the measurement setup to illustrate the impact of practical deployment onto the integrated PLCLiFi link. In this case, port A of the VNA is connected to the PLC coupler 1. The PLC coupler 1 is then connected to a wall socket using a 50 cm NYM-J cable. The signal goes through a PLC connection inside the wall and reaches the next socket on the same wall. From there, it is connected to the PLC coupler 2, with another 50 cm NYM-J cable. A LiFi link is finally added with variable link lengths as before, where both OFEs are located in the center of the room in a LoS configuration. In Fig. 6, the normalized amplitude response is shown. At low frequencies, it is similar to an isolated single powerline. However, as frequency increases, there are two distinct notches around 30 and 88 MHz with an attenuation down to -50 and -22 dB, respectively. These notches are attributed to multi-path reflections in the powerline grid deployed inside the

wall. Taps in the power line, possibly from the cable installation inside the wall which is nearby the floor but goes also up to the ceiling, may lead to such destructive interferences. Based on the PLC multi-path model from Zimmermann and Dostert [27], the destructive interference occurs at $f_n = \frac{c}{2L_{eff}}$ where L_{eff} is the effective difference between the length of the direct and reflected path and c is the speed of light in the deployed power cable.

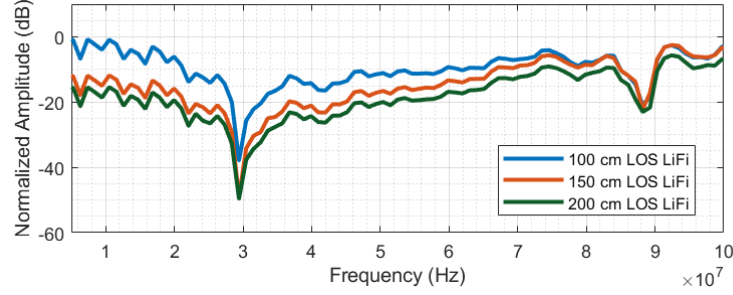


Fig. 6: Normalized frequency response of a real PLC channel and different lengths of LiFi channel [16].

4.2 Characterization of Noise and interference

The results have been published as [P1] in WFCS 2025.

4.2.1 Objective:

- Systematic measurements of interference and noise up to 300 MHz, which provide fundamental insights how PLC and LiFi contribute to the impairments in the cascaded link.

4.2.2 Experimental setup:

To explore noise propagation from LiFi through PLC, an uplink scenario is studied. After receiving additive white Gaussian noise via the OFE Rx, the signal passes through the PLC coupler 1, then through the powerline cable, which acts as an antenna and collects ambient interference, followed by PLC coupler 2 before the compound signal is measured at the spectrum analyzer. Noise and interference are measured using the same setup with a spectrum analyzer Rohde and Schwarz model FSU 1166.1660.67 at a resolution bandwidth of 10 kHz. The root mean square function is used to record the noise and interference power over a typical one minute measurement interval.

4.2.3 Results:

As can be observed in Fig. 7, the noise in the cascaded 100 cm LoS LiFi and 10 m PLC links is measured up to 300 MHz in the Fraunhofer HHI building under two different environments: the laboratory on the south side of the 11th-floor and at the ground floor. Across all measurements, the noise level is significantly above the noise floor of the spectrum analyzer at -96 dBm with a resolution bandwidth of 10 kHz. In both scenarios, noise is mainly due to the LiFi link having a 3 dB bandwidth of around 90 MHz. Although the PLC link alone acts as an antenna, picking up interference from open prototype devices and other experimental setups in the lab, the overall noise in the combined PLC–LiFi link is dominated by the LiFi Rx itself. In the laboratory environment, minor interference is visible within the FM radio band (88.5–108 MHz), originating from the Berlin TV tower located about 5 km away. The last curve shows the noise of the 100 cm LoS LiFi and a real power grid at the ground floor. It is basically the band-limited noise from

the LiFi Rx filtered through the powerline fading channel while interference from the powerline grid can be neglected.

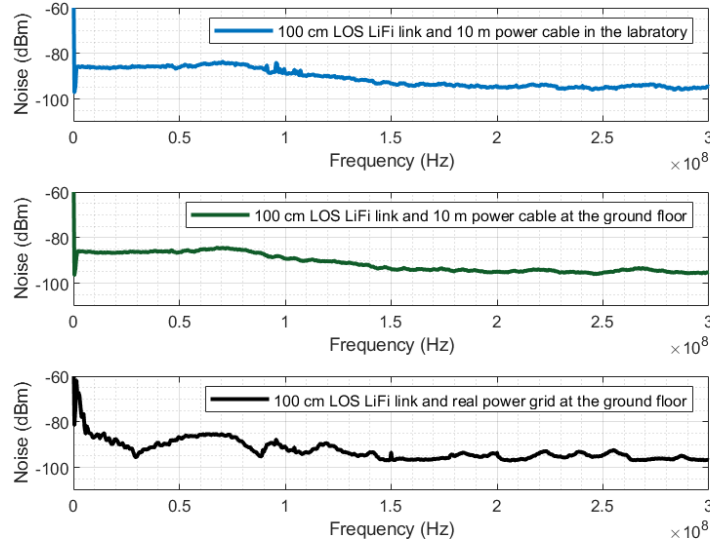


Fig. 7: Noise of the cascaded 100 cm LoS LiFi and 10 m power cable in two different environments and the cascaded 100 cm LoS LiFi and real power grid in an up-link scenario [16].

4.3 Throughput and Capacity Analysis of LiFi-over-Powerline

The results have been published [P2] in the 33rd International Conference on Software, Telecommunications and Computer Networks (SoftCOM 2025).

4.3.1 Objective:

- A complete link-level performance evaluation is presented using both uniform and adaptive bit-loading, including capacity estimates, throughput measurements, and BER analysis before and after forward error correction (FEC).

4.3.2 Experimental setup:

A Spectrum arbitrary waveform generator (AWG) is used to send packets containing 512 OFDM symbols with a random data at a sample rate of 400 MS/s. As shown in Fig. 8, the signal is first transmitted from AWG to the PLC coupler through a SMA cable. The PLC coupler 1 is then connected to a wall power outlet using a 50 cm NYM-J cable. The signal via a PLC link inside the wall reaches the next power outlet on the same wall. From there, it is connected to the PLC coupler 2 with another 50 cm NYM-J power cable. Then the LiFi link Generation 1 (as explained earlier) is added. Various lengths of LOS LiFi links are investigated in the experiment. Finally, the output of an optical Rx, which emulates a mobile device, is connected to a LeCroy WavePro 804HD oscilloscope running at a sample rate of 5 GS/s.

The transmitted signals are modulated using DCO-OFDM with a bandwidth of 100 MHz, an FFT size of 1024, and cyclic prefixes of 128 samples. The 11 subcarriers at the lowest frequencies are not used. Adaptive bit and power loading is implemented using the optimal Krongold algorithm [28] which has low complexity, likewise. The ability to assign different orders of M-quadrature amplitude modulation (QAM) for each OFDM subcarrier is known as “bit loading”. In

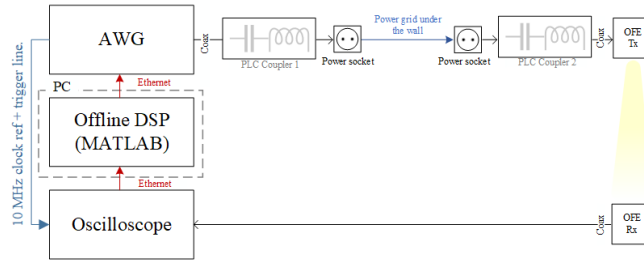
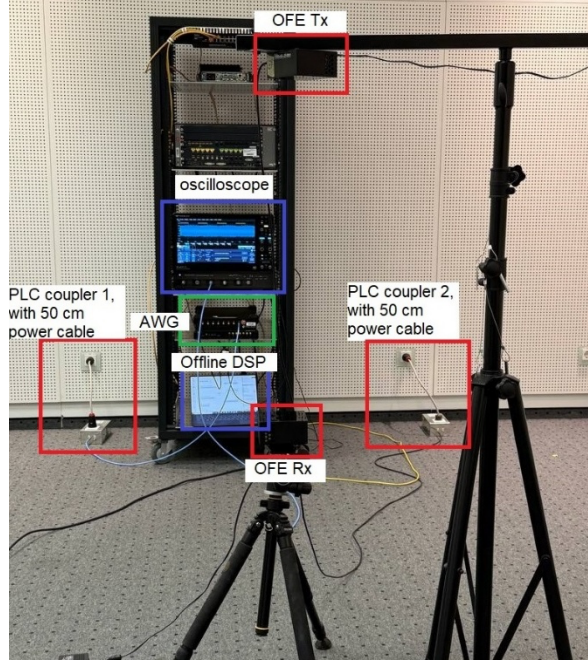


Fig. 8: (up) LiFi over powerline experimental setup (bottom) Block diagram [26].

this method, the lowest modulation order of binary phase shift keying is considered, and we calculate the error value magnitude to achieve a specific SNR level for each subcarrier. For a given target BER, the Krongold algorithm determines the number of bits/symbol/subcarrier according to the SNR. The experiments are conducted using an offline processing approach which runs in two phases. In the first phase, the data with a constant modulation format is transmitted to estimate the SNR per subcarrier. In the second phase, we used the output of The Krongold algorithm to encode data according to the G.9960 specification, including FEC based on low density parity check (LDPC) codes. This setup allows us to precisely measure pre and post-FEC BERs and fully analyze the link performance.

4.3.3 Results:

- Capacity estimation

Shannon-Hartley's channel capacity theorem is often applied at the beginning of any link budget analysis to provide an upper bound on the data rate given a certain bandwidth and SNR. Shannon capacity formula captures how each subcarrier contributes differently to the overall capacity. In our study, B and N are 100 MHz and 1013 subcarriers, respectively. The capacity is given by:

$$c = \sum_{n=1}^N \frac{B}{N} \log_2^{(1+SNR_n)}, \quad (1)$$

Figure 9 illustrates measured SNR responses across an 100 MHz bandwidth for four distinct configurations: configuration (A) has relatively stable SNR around 30 dB across the entire bandwidth. Configuration (B) shows uniform SNR performance around 25 to 28 dB across the measured spectrum. The cascaded 10 m PLC with 100 cm LoS LiFi as configuration (C) presents combined channel effects, starting around 28 dB at lower frequencies, decreasing gradually toward approximately 20 dB at higher frequencies. Finally, configuration (D) demonstrates considerable frequency-selective fading, with SNR varying significantly between roughly 10 to 30 dB. This response indicates pronounced channel impairments due to interference and reflections in energized power grids, which was also visible in the corresponding CFR. Based on the measured SNR, the result of capacity estimation are shown in Table I. The upper bound capacity of LiFi-only link is about 871.50 Mbit/s while it decreases to 784.87 Mbit/s when the optical wireless link is combined with power grid as its backbone.

- Throughput

Table II presents the pre- and post-FEC data rates and BERs for proposed link configurations. The throughput is measured for all links using both, uniform and adaptive bit-loading schemes. The QAM modulation with a variable order M (ranging from 2 to 256) is investigated, and for each case, the highest modulation order that enables error-free transmission after LDPC FEC decoding is selected. As seen in Table II, the maximum supported QAM modulation order for reaching error-free transmission with uniform bit-loading on all subcarriers for configurations A, B, and C is 64, resulting in pre- and post-FEC data rates of 506.250 and 421.875 Mbit/s, respectively. The corresponding pre-FEC BER for configurations (A), (B) and (C) are 7.502×10^{-4} , 1.683×10^{-3} , and 9.152×10^{-3} , respectively. In addition, for the power grid with a 100 cm LiFi link, the maximum supported QAM modulation order decreases to 16-QAM, yielding pre- and post-FEC data rates of 337.5s and 281.250 Mbit/s, respectively, with post-FEC BER of 4.115×10^{-3} . In the adaptive bit-loading scheme, the modulation order vary from 1 to 10 bits per subcarrier. A BER threshold of 10^{-2} is applied for an LDPC code with a word length of 4320 bits and a code rate of 5/6. All measured pre-FEC BERs are below the FEC threshold, ensuring reliable, error- free transmission after LDPC decoding. This confirms the robustness of bitloading with LDPC coding across different link conditions. Specifically, for the real power grid with the 100 cm LiFi link, when applying the adaptive bit-loading algorithm, the throughput almost doubles from 281.250 to 492.188 Mbit/s.

TABLE I: Expected capacity according to equation 1

Link Configuration	Capacity (Mbit/s)
(A) 10 m PLC	1038.23
(B) 100 cm LiFi	871.50
(C) 10 m PLC and 100 cm LiFi	817.62
(D) Power grid and 100 cm LiFi	784.87

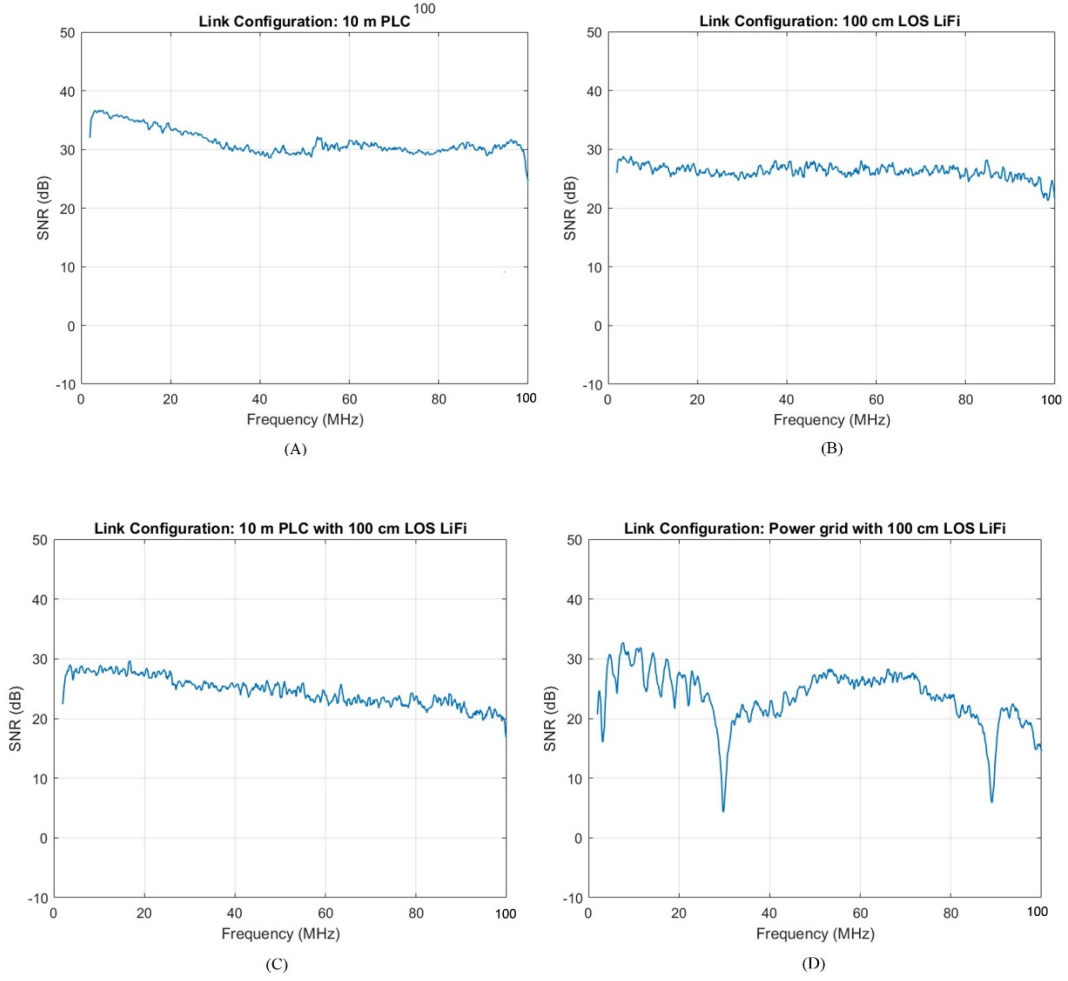


Fig. 9: SNR versus frequency for four different link configurations [26].

TABLE II: Pre- and post- FEC datarate and BER for four different link configurations

Link Configuration	Modulation	Pre-FEC data rate (Mbit/s)	Post-FEC data rate (Mbit/s)	Pre-FEC BER	Post-FEC BER
(A) 10 m PLC	64 QAM	506.250	421.875	7.502×10^{-4}	0
	Bit loading	787.500	656.250	2.701×10^{-3}	0
(B) 100 cm LiFi	64 QAM	506.250	421.875	1.683×10^{-3}	0
	Bit loading	675.000	562.500	7.869×10^{-3}	0
(C) 10 m PLC with 100 cm LiFi	64 QAM	506.250	421.875	9.152×10^{-3}	0
	Bit loading	646.875	539.062	1.003×10^{-2}	0
(D) Real power grid with 100 cm LiFi	16 QAM	337.500	281.250	4.115×10^{-3}	0
	Bit loading	590.625	492.188	7.900×10^{-3}	0

4.4 Performance Evaluation of Fischer–Huber Bitloading Algorithm for LiFi over PLC

The results have been submitted as [P5] for WFCS 2026.

4.4.1 Objective:

- A link-level performance evaluation of the Fischer–Huber algorithm for adaptive bit-and-power loading over the cascaded PLC–LiFi channels, focusing on BER and achievable throughput under a fixed target datarate constraint.

- The first experimental demonstration of Fischer–Huber margin-adaptive bit loading in a cascaded PLC-LiFi link, explicitly targeting reliability-oriented industrial wireless operation instead of throughput maximization.

4.4.2 Experimental setup:

The experimental setup is a LED based LiFi-PLC system similar to the previous one which is explained in section 4.3.2.

4.4.3 Results:

The results confirm that Fischer–Huber bit loading can successfully mitigate the impact of spectral notches introduced by the power grid, enabling stable and reliable LiFi over PLC transmission at several hundred Mbit/s. We won't go into more details here because the results are submitted now to the WFCSS 2026 conference.

4.5 1 Gbit/s LiFi over Powerline using VCSEL Arrays

The results have been submitted as [P4] for 15th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP 2026).

4.5.1 Objective:

- Compare LED and VCSEL-based LiFi transmission over powerline with OFDM and adaptive bit and power-loading to reach 1 Gbit/s for the first time.
- Performance evaluation for different fixed and wireless link lengths to gain insights into the potential and next steps towards practical deployment

4.5.2 Experimental setup

The experimental setup is almost the same as explained before but in this work we use LiFi Generation-2. One of the main problems in the LED-based LiFi setup is the 3 dB bandwidth of the LED based Tx that is about 90 MHz, limiting the data rate significantly. In the second generation of LiFi, the LED-based Tx is replaced with VCSEL arrays offering a data rate of 1 Gbit/s for a 30 cm PLC-LiFi link.

4.5.3 Results:

Over a power grid deployed inside the wall and a subsequent LED-based LiFi link length of 80 cm, a net data rate of 516 Mbit/s after FEC decoding is reached. Using a VCSEL-based optical hop at the same received power (at a 40 cm distance), the net rate increases to around 924 Mbit/s. Moreover, we managed to reach 1.007 Gbit/s using LiFi over powerline for the first time for a 30 cm link length with a single photodiode Rx. We won't go more into details here because the results are submitted now to the CSNDSP 2026 conference. However, the VCSEL performance was presented in ECOC 2025 [29]

4.6 Imaging APD Receiver for Multi-Gbit/s Optical Wireless Communication with Angular Diversity

The results have been published as [P3] in Optical Fiber Communication Conference and Exhibition 2026 (OFC 2026).

4.6.1 Objective: To

- demonstrate a high-speed short-range optical wireless link based on a high-power VCSEL array Tx and a 12×12 APD imaging Rx, achieving multi-Gbit/s data rates over a 1 GHz bandwidth.

- investigate angular diversity and misalignment tolerance by evaluating system performance under Rx rotation ($\pm 30^\circ$) and implementing dynamic pixel selection based on the highest SNR.
- validate the feasibility of an imaging APD array Rx for next-generation laser-based LiFi systems, enabling robust, wide-beam, mobility-supporting OWC without the Tx beam steering overhead.

4.6.2 Experimental setup

In this work we introduce and evaluate the LiFi Generation-3. The schematic of our experimental setup is shown in Fig. 10 (a). Figure 10 (b) shows images of the VCSEL and APD array with their respective driver and the Rx circuitry. At the Tx side, nine Brightlaser VD-940V-140M-1C-5A1VCSEL arrays are used with a peak wavelength of 940 nm and an optical transmit power of 140 mW at a forward current of 89 mA each. Diffusers are mounted on each VCSEL array providing eye-safe half-power beam-widths of 60° and 45° in the x- and y-direction, respectively, to broaden coverage and relax the Tx alignment requirements. An effective average optical output power of 660 mW is measured for the whole Tx with the VCSEL arrays driven serially at a bias current of 68 mA. At the Rx side, a 12×12 imaging APD array is used. The imaging properties of various lenses are carefully characterized to select the one with the highest collected power. Accordingly, an aspheric Fresnel lens with 15 mm-aperture and only a 3 mm focal length is mounted in front of the APD array aligned with the center of the detector matrix. The APD array has an overall size of $5 \times 5 \text{ mm}^2$ to realize a high FOV. The array is custom-designed on a complementary metal oxide semiconductor (CMOS) chip by Fraunhofer HHI and Broadcom-Avago for the next generation, laser-based OWC systems. 144 detectors are arranged in four quadrants with 6×6 pixels each. The reverse bias voltage is 55 V. Each pixel in the array has $400 \times 400 \text{ }\mu\text{m}^2$ size with a filling factor of 95% and its own TIA with a 1.5 GHz bandwidth. In an imaging Rx, ideally, each pixel in the array is designated to address a different sector in the room. On the APD array, pixels can be individually selected or grouped up by row and column so that on-chip clustering is possible in each quadrant. The combined signals can be readout via differential outputs for each quadrant. In this work, we only use one quadrant (A or D) at a time to realize angular diversity in the horizontal dimension. For LoS (0°) measurements, we combine the positive output of quadrant A and the inverting output of quadrant D, since the optimal pixels are between both quadrants (Fig. 10 (c)). Otherwise, within a selected quadrant, only one pixel is addressed at a time, to minimize capacitance and allow the TIA to operate at its maximum bandwidth. In a LoS scenario, switching between the pixels can be regarded as steering the active Rx direction towards the Tx in a "grid-of-beams" approach widely used at base station antennas in mobile networks. Pixel selection and parametrization of the Rx front-end are performed by a local computer via the serial programming interface (SPI) of the APD array, to optimize all settings before taking measurements. OFDM signals with an FFT size of 1024, and cyclic prefix of 128 samples are used at a peak-to-peak voltage of 700 mV, and the extreme values are clipped digitally at four times the signal amplitudes' standard deviation. The transmitted OFDM-signal follow the OFDM-PHY defined in IEEE ITU-T G.9960 PHY at 1 GHz bandwidth. 11 subcarriers at the lowest frequencies are not used. A LDPC code with a word length of 4320 bits is used for FEC. Adaptive bit and power loading is implemented using the Krongold algorithm. A Keysight M8190A AWG is used to feed frames containing 512 OFDM symbols with random data into the Tx prototype at a sample rate of 4 GS/s. The Rx is connected to a LeCroy WavePro 804HD oscilloscope running at 20 GS/s. We study (i) a baseline 20 cm LoS link, (ii) the same LoS link where power is magnified by a lens between Tx and Rx and (iii) a 20 cm LoS link under varying Rx angles to demonstrate the impact of angular diversity on coverage and throughput.

4.6.3 Results:

Figure 11 (a) shows the measured SNR as a function of frequency for a 20 cm LoS link using a VCSEL–APD array without the optical lens between the Tx and the Rx. For this case, a post-FEC data rate of 2.395 Gbit/s is achieved at the target BER before FEC of 4.5×10^{-3} . In the second configuration (blue curve), a Thorlabs FRP251 plano-convex lens with 2-inch diameter and 51 mm focal length is positioned in front of the APD array to converge the transmitted optical



beam onto the Rx aperture. The lens significantly improves the received optical power and leads to a flattened SNR profile across the full 1 GHz bandwidth, resulting in pre- and post-FEC data rates of 5.273 and 4.395 Gbit/s, respectively, at the same BER target. This observation indicates that optical coupling between the VCSEL array and the APD Rx can be enhanced to increase the achievable throughput. Figure 11 (b) shows the bit- and power-loading profiles of 20 cm LoS VCSEL–APD links without and with the optical lens between the Tx and the Rx. The link adaptation algorithm allocates 1–7 bits per subcarrier while subcarriers with SNR below 3 dB are not modulated. Averaged over 1013 active subcarriers, the bit loading reaches 5.999 with and 3.269 bits/subcarrier without an optical lens, respectively. Figure 11(c) presents the measured Pre-FEC and Post-FEC data rates versus the Rx’s orientation, demonstrating that angular diversity is supported by the imaging APD array Rx. During this measurement, the Tx remains fixed, while the Rx is rotated from -30° to $+30^\circ$. Despite the change of the incidence angle, the link maintains nearly the same net data rate of more than 2.3 Gbit/s. At each angular position, the pixel yielding the highest SNR within the active region is selected. Selecting the best pixel on the array for the given link direction towards the Tx enables robustness in mobile scenarios, while more than 1 GHz bandwidth can be realized. As illustrated in Fig. 11 (c), the imaging Rx is divided into four quadrants (A–D), when the Rx is rotated and the dominant illumination spot shifts between the quadrants. For example, at $+30^\circ$, the optimal pixel is located in quadrant D, while at -30° it lies in quadrant A. Adaptive quadrant-based pixel selection effectively aligns the link direction and thus enables stable high-speed communication across a wide FOV.

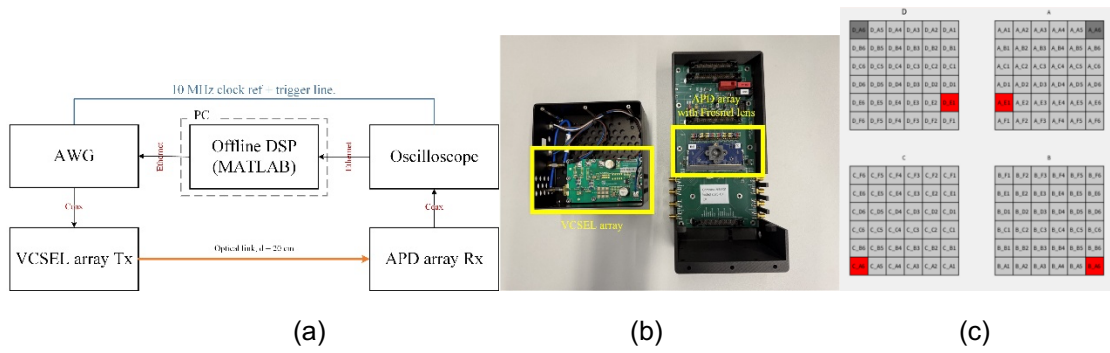


Fig. 10: (a) Experimental setup for the 20 cm LoS VCSEL–APD link, (b) 9 VCSEL arrays (left) and APD array on a carrier board (right), and (c) quadrant layout of the imaging Rx showing adaptive pixel selection. The gap between quadrants in the figure is an artefact. It does not apply to the physical APD array [P3].

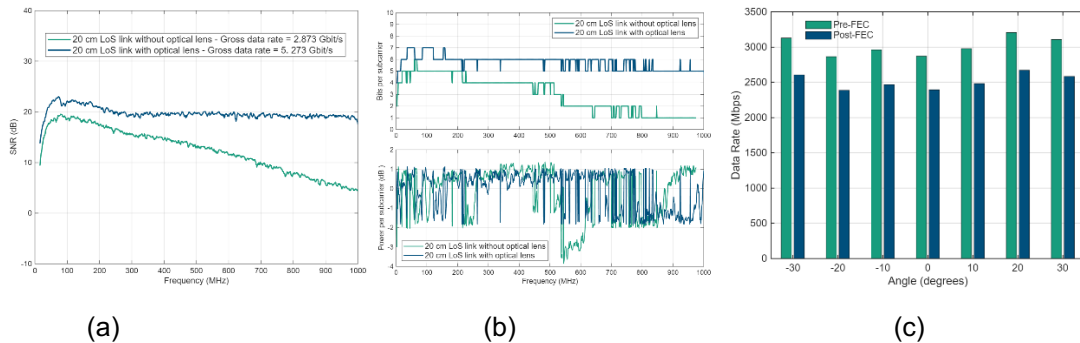


Fig. 11: (a) Measured signal-to-noise ratio, (b) bits and power loaded per subcarrier at the highest error-free post-FEC data rate., and (c) pre- and post-FEC data rate for different angles [P3].

4.7 Project showcase: Live demo in mobile world congress (MWC 2025)

PLC/LiFi demo as OWIN6G project deliverable D2.2: HHI demonstrated a second real-time prototype of LiFi over Powerline. It implemented the amplify-and-forward approach (investigated in OWIN6G), which was simpler and allows cost-efficient integration into lighting infrastructure. The demo attracted significant interest from industry and academia. A major outcome was to show how small the PLC-LiFi access point can be if the required electronics is integrated. There is, however, more work to be done, including power reduction and the integration within mobile devices. Moreover, tests with multiple access points, connected to the same powerline, are planned. This is helpful to realize spatial diversity needed to overcome LoS blockages.



Fig. 12. Live demo of AF PLC-LiFi, MWC 2025, Barcelona, Spain.

4.8 List of publications

- [P1] A. Pouralizadeh, S. Maravanchery Mana, K. L. Bober, V. Jungnickel, A. Tonello, C. Giachoudis, and A. Khalighi, "Characterization of LiFi-over-powerline channels for industrial Internet-of-Things applications," in *Proc. 2025 IEEE 21st Int. Conf. Factory Communication Systems (WFCS)*, 2025, pp. 1–4.
- [P2] A. Pouralizadeh, K. L. Bober, V. Jungnickel, and A. Tonello, "Throughput and capacity analysis of LiFi-over-powerline," in *Proc. 2025 Int. Conf. Software, Telecommunications and Computer Networks (SoftCOM)*, 2025, pp. 1–6.
- [P3] A. Pouralizadeh, M. J. Bode, G. Boniello, M. Hinrichs, C. Kottke, S. Cwalina, R. Freund, and V. Jungnickel, "Imaging APD receiver for multi-Gbit/s optical wireless communication with angular diversity," in *Proc. Opt. Fiber Commun. Conf. (OFC)*, 2026.
- [P4] A. Pouralizadeh *et al.*, "1 Gbit/s LiFi over powerline using VCSEL arrays," **submitted** to *15th Int. Symp. Communication Systems, Networks and Digital Signal Processing (CSNDSP)*, 2026.
- [P5] A. Pouralizadeh, D. Goodson, V. Jungnickel, L. M. Giraldo, and J. Perez Soler, "Performance evaluation of Fischer–Huber bitloading algorithm for LiFi over PLC," **submitted** to *2026 IEEE Int. Conf. Factory Communication Systems (WFCS)*, 2026.

5. Summary

This deliverable presented the results of Task 2.2 in the OWIN6G project, focusing on the development and validation of a cascaded PLC–LiFi system as a cost-effective backbone for wireless sensor networks in existing buildings. The study demonstrated that PLC can be successfully combined with LiFi to provide high-speed indoor wireless connectivity without installing new cables. Detailed channel measurements and noise analysis were performed, showing that the LiFi link mainly determined the overall system performance, while powerline effects introduced frequency-selective fading in real deployments. Using OFDM with adaptive bit and power loading, stable data rates of several hundred Mbit/s were achieved, and performance was significantly improved compared to uniform loading. By upgrading the system from LED-based TxS to VCSEL arrays, the first 1 Gbit/s LiFi-over-powerline transmission was demonstrated. In addition, a new LiFi system using a VCSEL array and an imaging APD Rx achieved multi-Gbit/s data rates and showed robustness against the Rx misalignment through angular diversity. Overall, the results confirmed that PLC–LiFi integration was a feasible and scalable solution for high-speed indoor communication in future 6G scenarios.

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