Enhance Lighting for the Internet of Things

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Industry Demonstrators – LiFi/5G and Positioning

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Abstract

This document reports on the ELIOT demonstrators for LiFi/5G in industry and LiFi for positioning.

The scope of the Industrial Communication demonstrator is to demonstrate reliable wireless network connections for factory applications between end user devices and an application server. Important objectives are the combination of LiFi with 5G to reach flexibility, reliability, coverage and high throughput for fixed and mobile devices on the shop floor and the coverage of machine with LiFi.

The Positioning demonstrator in ELIoT shows the feasibility of LiFi-based positioning in an industrial environment. Objective is to localize a fixed and a moving object on a shop floor, which is covered by LiFi. Important KPIs are accuracies in cm range and the use of communications standards for the distance estimation to ease integration.

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Index of terms

5G	5^{th} Generation of Mobile Communication
AFE	Analog Front End
AP	Access Point
BB	Base Band
DSP	Digital Signal Processing
ECO	Electro-Optical Communications
ELIoT	Enhance Lighting for the Internet of Thinks
GPS	Global Positioning System
FWA	Fixed Wireless Access
HB	High Bandwidth
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Thinks
ITU	International Telecommunication Union
LC	Light Communication
LiFi	Light Fidelity (Optical wireless communication)
LED	Light Emitting Diode
MAC	Media Access Control
MIMO	Multiple In Multiple Out
OWC	Optical Wireless Communication
PHY	Physical Layer
RF	Radio Frequency
Rx	Receiver
Tx	Transmitter
VLC	Visible Light Communication
5G-NR	5G-new radio
UDP	User Datagram Protocol
UE	User Entity
URLLC	Ultra-reliable low latency communication

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1. Industry Communication Demonstrator

1.1. Motivation for wireless industrial communication

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 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 1, 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.

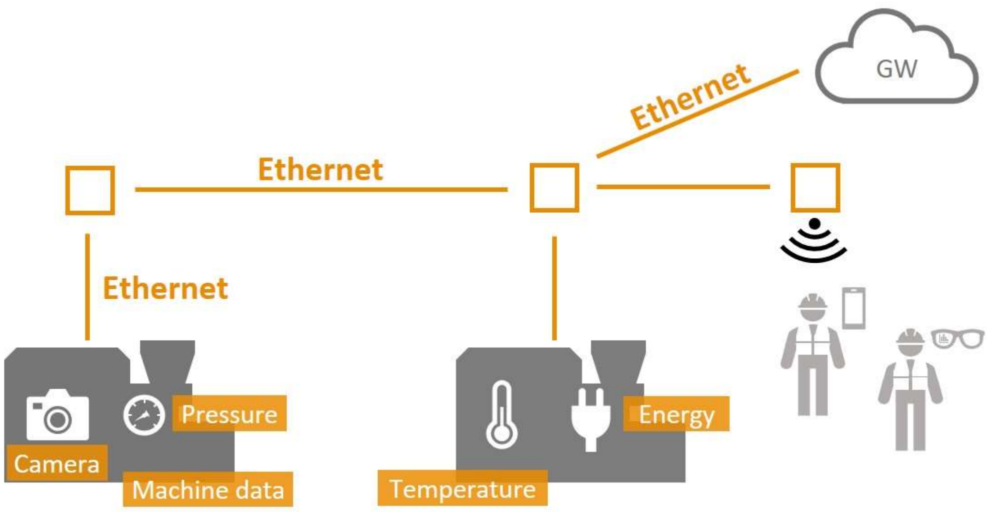

Figure 1 Communication on the shop floor via cable-based Ethernet and Wi-Fi

1.2. Scope of the demonstrator

The scope of this demonstrator is to demonstrate reliable wireless network connections for factory applications between end user devices and an application server. Within this scope, LiFi is combined with 5G to reach flexibility, reliability, coverage and high throughput for fixed and mobile devices on the shop floor. Scenarios for the application of LiFi and LiFi with 5G in factories are detailed in section 5.1.2 of deliverable 6.1. In this section, we describe the scope of the demonstrator realized and the gap to the demonstrator planned.

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Smart glasses enable technicians on the shop floor to work with both hands on a machine while viewing live operational data or getting remote assistance. An externally located technician or global expert supports the local technician with instructions via an interactive video stream. Such a video stream is shown in Figure 2. The local technician stays with Microsoft HoloLens 2 in front of the cabinet and communicates across Microsoft Teams with the externally located technician. The externally located technician is shown bottom in the right window. Both technicians can see the cabinet and work together in this view. The externally located technician instructs the local technician and has drawn the virtual orange arrows in the middle to support the audio instruction with visual elements. The local technician follows the instructions and measures.

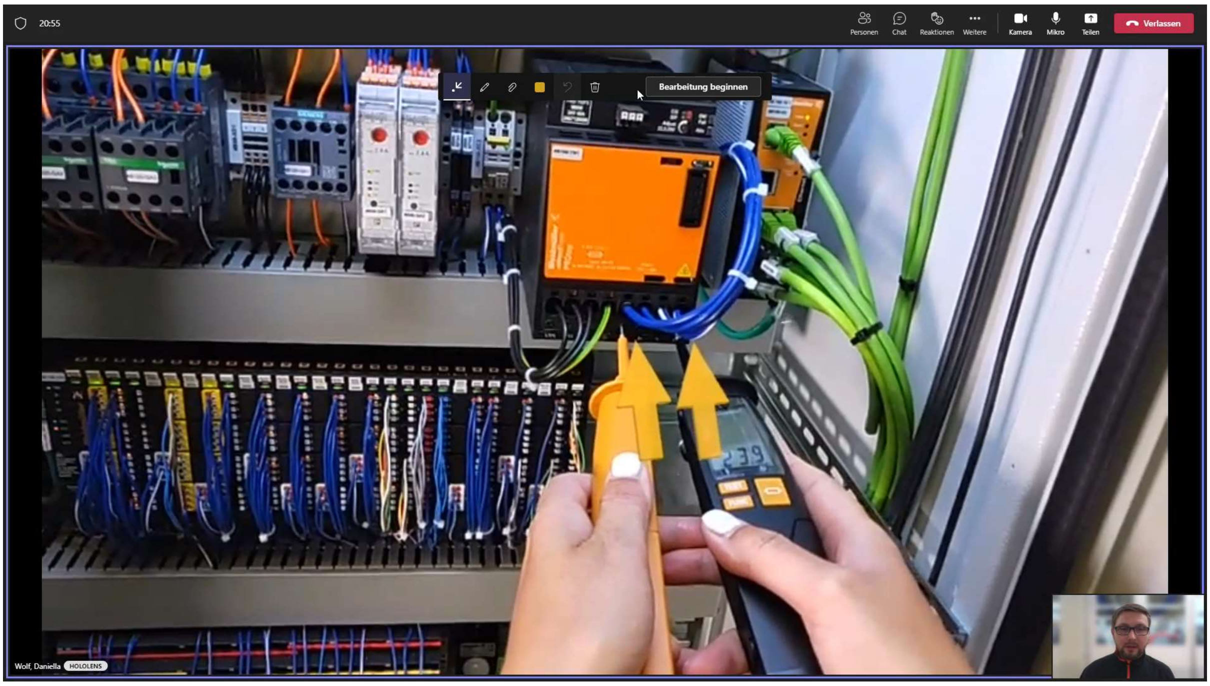

Figure 2 Remote assistance with Microsoft Teams and Microsoft HoloLens 2 at a cabinet

The system architecture illustrated in Figure 3 is the basis to demonstrate the story line. Ideally, upon availability, end user devices support both interfaces LiFi and 5G new radio and can switch between both interfaces with seamless handover, i.e., network coverage is always available via 5G-NR, but if LiFi is available, the network traffic use LiFi instead of 5G-NR.

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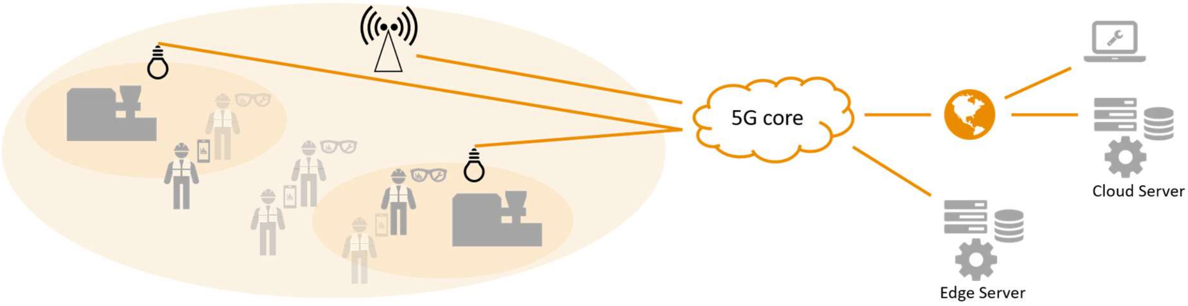

Figure 3 Architecture of the demonstrator planned with 5G SA RAN and two LiFi APs with cabled backhaul: staffs move between LiFi cells

In the envisaged scenario described in section 5.3.1 of deliverable 6.1, the demonstrator would have been setup in Weidmüller's factory with 5G-NR and two LiFi cells as shown in Figure 3. Due to COVID 19 the demonstrator was subdivided. Fraunhofer HHI is focused on developing, dimensioning, and testing the LiFi AP and LiFi user equipment (UE), Fraunhofer FOKUS is focused on the integration of LiFi into its Open5GCore as a non-3GPP access technology, and Weidmüller is focused on realizing the industrial scenario application and to evaluate the compatibility of LiFi with real-time Ethernet protocols, but the evaluation of real-time Ethernet protocols with 5G is beyond the scope of this demonstrator because the release of the Open5GCore used does not guarantee determinism and ultra-reliable low latency communication (URLLC). Finally, it was not possible to setup the final demonstrator in Weidmüller's factory due to COVID 19 and the associated limitations and contact restrictions. Instead, the demonstrator is setup at Fraunhofer HHI with 5G and one LiFi cell to evaluate vertical handover between LiFi and 5G. Furthermore, a LiFi link is installed at Weidmüller to evaluate the compatibility of LiFi with real-time Ethernet protocols.

1.3. Demonstrator setup

The demonstration set-up follows copes with the constraints coming from the geographic separation of the Fraunhofer FOKUS and HHI institutes, which each provide specific technologies required for the demonstration, i.e., that 5G radio cells are not available at HHI for integrated testing at one single geographic location. Also, LiFi components could not be brought to FOKUS due to institute-specific-COVID regulations. As such, the final demonstrator integrates simultaneously 5G and LiFi, each deployed at different geographic locations interconnected via dark fibre. As in the originally planned industrial demonstrator, 5G would have been deployed as such to providing continuous radio coverage in the factory, the set-up shown in the following figure technically replicates the originally planned demonstrator. The two institutes are connected via a dense wavelength division multiplexing (DWDM) system, which provides a transparent layer-2 (Ethernet) connection as shown at the far right

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side of Figure 4. The 5G/LiFi router is located at HHI. Its LiFi uplink is connected towards the DWDM system and is placed on a dedicated VLAN with VLAN ID xxx, which is then routed at FOKUS into a compute and storage blade system where the 5G core with its N3IWF is situated. The tricky part in the figure comes from the 5G-based uplink of the router located at HHI. The NATed network behind the CPE, geographically located at FOKUS, is extended via a dedicated VLAN from FOKUS towards HHI. This allows to have the 5G/LiFi router to be collocated with the real LiFi hardware at HHI, while the data for the 5G-based uplink is carried over that VLAN with VLAN ID yyy to FOKUS, where it reaches the commercial off-the-shelf CPE. This CPE at FOKUS connects over 5G new radio (100 MHz in N78 band, 3700 – 3800 MHz) to a gNodeB. The latter is attached to the 5G core running on the blade center. This set-up hence allows the 5G/LiFi router to communicate over real LiFi hardware located at HHI or over real 5G SA NR components located at FOKUS. For the LiFi set-up, four fixed LiFi ceiling units spanning the LiFi cell and the mobile unit at Fraunhofer HHI. The 5G/LiFi router is placed on a lab cart (see Figure 5) and can thereby be moved within and outside the coverage area of LiFi. As the CPE, to which the LiFi router is attached to, is not moved and thus always remains within the coverage area of the 5G gNodeB (at Fokus), the 5G/LiFi router has all the time an alternative, 5G-based uplink to conduct a handover to in case the LiFi link is interrupted.

For the trial, smart glasses (Microsoft HoloLens 2) acting as the user terminal is attached to the 5G/LiFi router.

In addition to those two VLANs, a third VLAN with VLAN ID zzz is established between FOKUS and HHI to provide an out-of-band remote administration access from FOKUS towards the router at HHI.

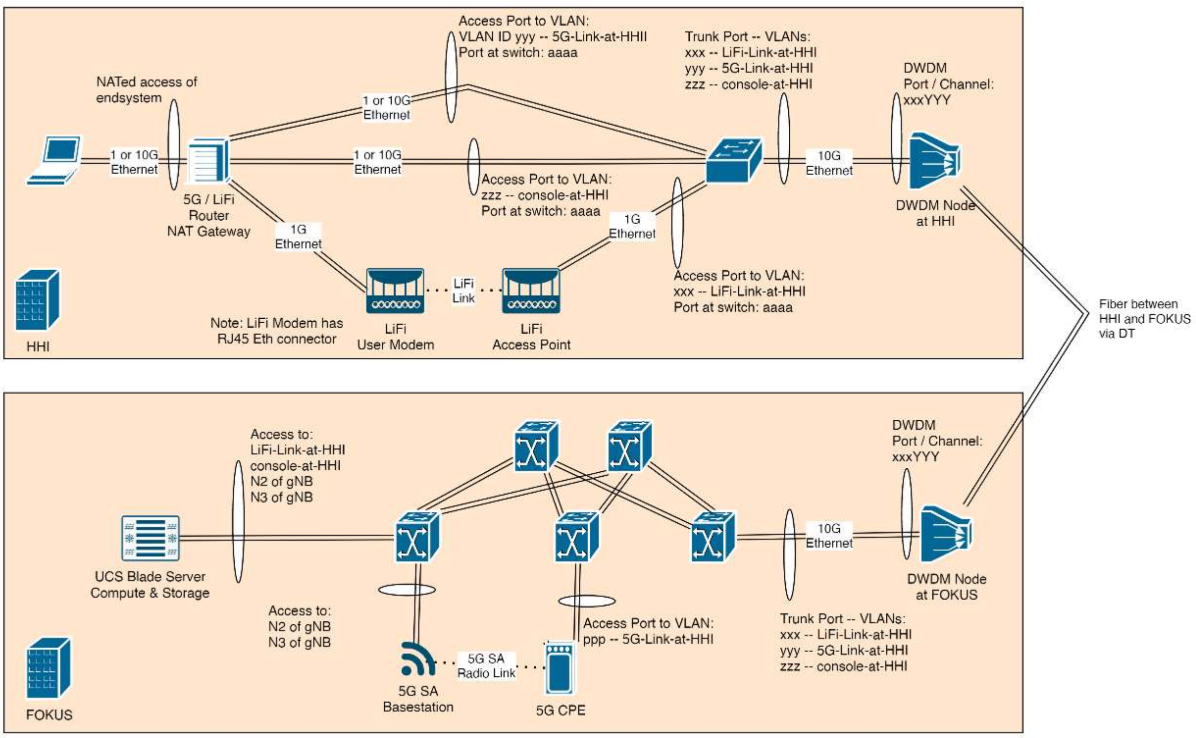

Figure 4 Network architecture for the testbed between Fraunhofer Fokus and HHI

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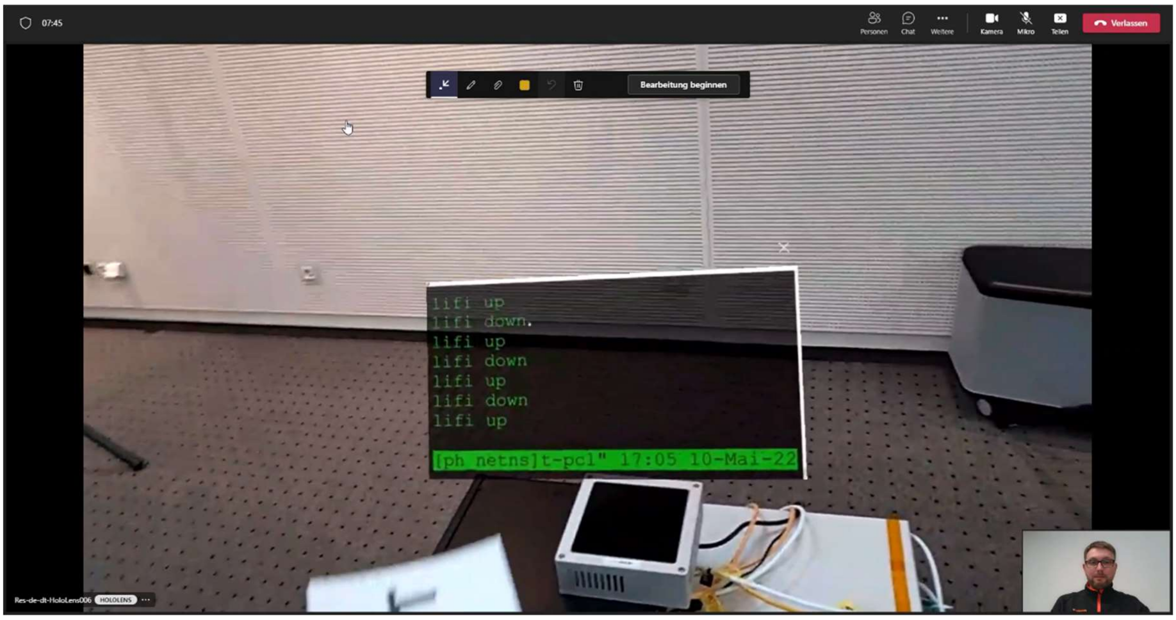
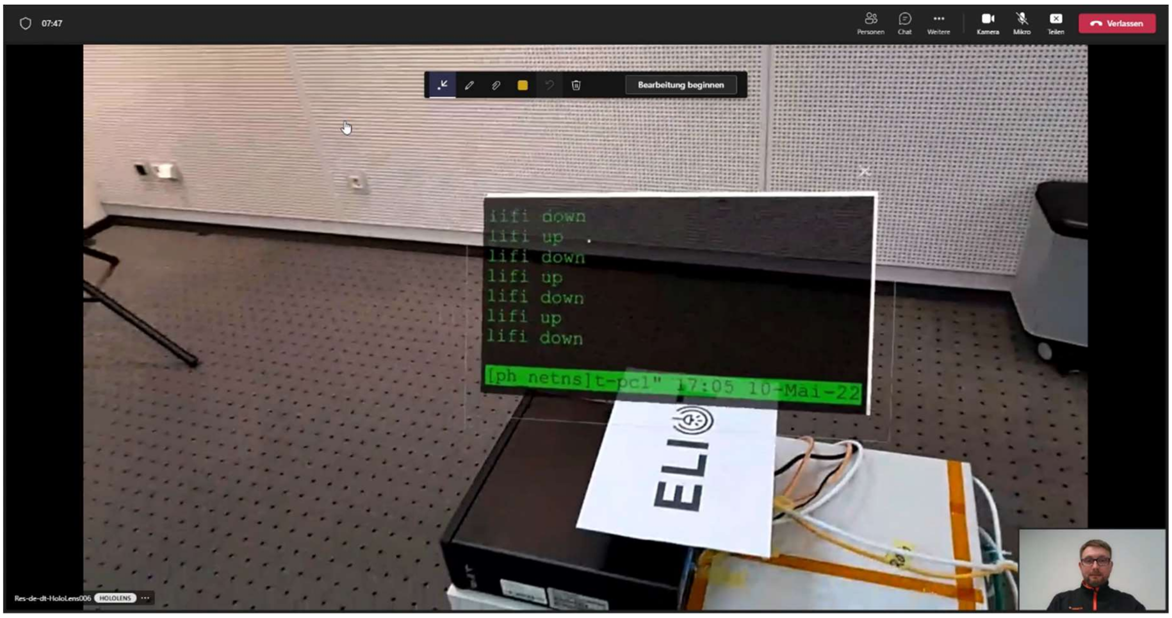
Figure 5 shows the demonstration at Fraunhofer HHI as seen through the HoloLens and as streamed via 5G or LiFi. The components involved in the trial are at the same time used to document the trials.

They show the ego perspective of a staff moving inside the LiFi cell with connected HoloLens, while an extern located staff (bottom right) guides the moving staff. It is the remote assistance scenario described above. The figures show in the center an augmented reality (AR) object. It is streamed via Microsoft Teams into the HoloLens and visualize in a terminal window the network connection status of the end user device (HoloLens). The mobile unit with 5G / LiFi Router NAT Gateway is below the terminal window.



a)



b)

Figure 5 Demonstration of vertical handover at Fraunhofer HHI with mobile unit in the center bottom with 5G / LiFi Router NAT Gateway and AR object that visualize network connection status: a) the LiFi link is up b) the LiFi link is down

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The HoloLens is connected through this gateway with the Internet. In Figure 5 a), line of sight is available and the LiFi link is up. In Figure 5 b), the LiFi link is down because the LiFi modem is covered with a sheet of paper and therefore, line of sight is not available. However, the network connection is available because LiFi down means “N3IWF: 5G-NR” is used and LiFi up means “N3IWF: LiFi” is used. This test demonstrates the vertical handover between LiFi and 5G using the N3IWF.

In another setup located at Weidmüller we are focused on industry protocols such as OPC UA and Profinet. Figure 6 a) shows the setup with two Hosts and two LiFi modules. Host A is an industry computer (IPC) that works in the first scenario as an OPC UA server and provides data. In a second scenario it works as a Profinet controller for Profinet RT. Host B works in the first scenario as an OPC UA client and consumes data from the OPC UA server. In the second scenario it works as a Profinet device for Profinet RT.

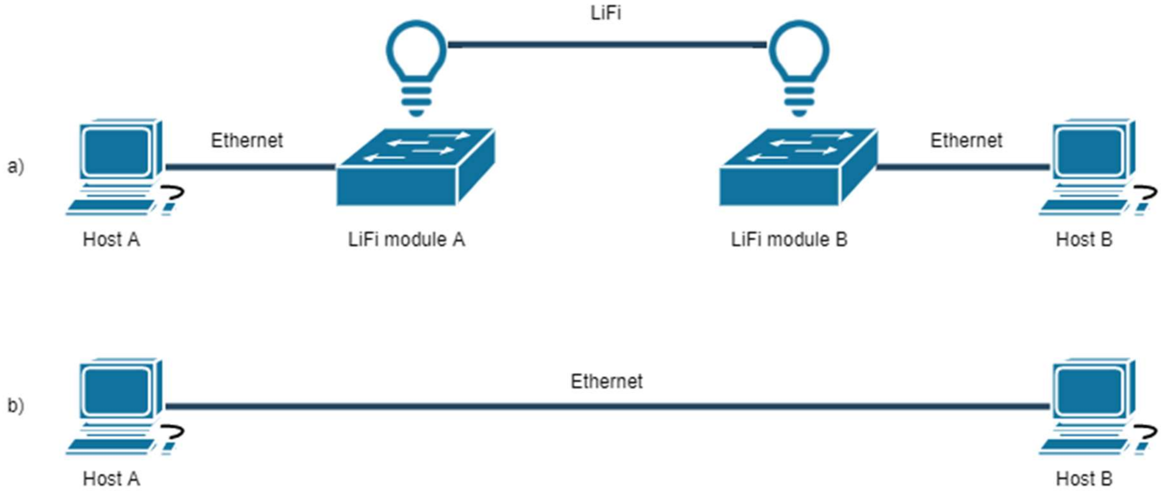

Figure 6 Setup for testing industry protocols a) with LiFi modules b) with Ethernet cable only

1.4. Measurement results

In a first step, the overall performance of only the LiFi link was evaluated. The uplink and downlink speeds as well as the coverage of the LiFi cell were measured. Figure 7 shows the data rates achieved in the LiFi cell. A peak data rate of more than 550 Mbit/s in the downlink and more than 350 Mbit/s in the uplink is achieved. With a spot radius of 1.25 m, an area of almost 5 m² can be covered with one LiFi access point. Within this LiFi cell, full mobility is possible without interruption. Even at the cell edges, the data rate in the downlink is around 100 Mbit/s. This shows that high data rates are possible in a coverage area of several square metres, which makes LiFi applicable for mobile communication in factories and for many new use cases.

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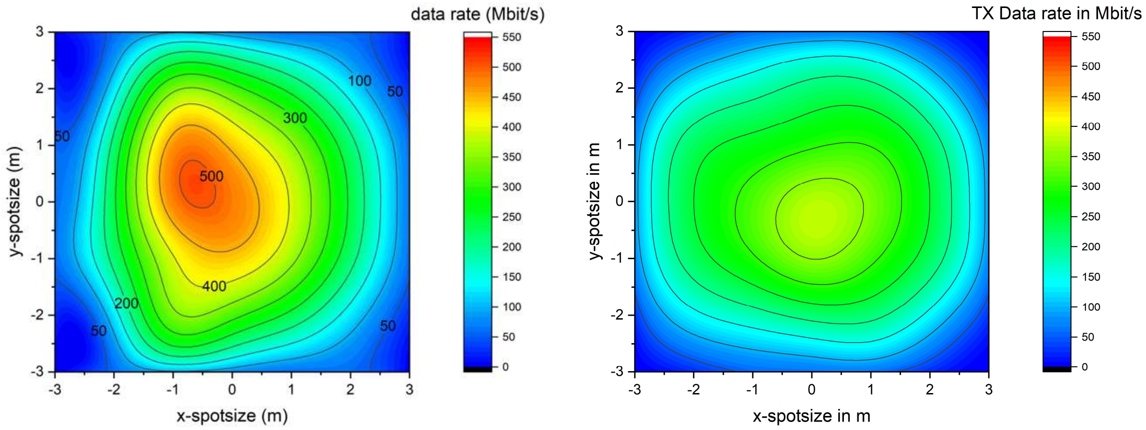

Figure 7 Coverage and gross data rates of LiFi cell.

With the demonstrator setup at Weidmüller shown in Figure 6 a) we have verified that LiFi can generally be used to transport data via OPC UA and Profinet. In the next step, we have compared the behaviour of a LiFi link between Host A and Host B, see Figure 6 a), with a wired link (CAT.5), see Figure 6 b), using Profinet RT. The application at the IPC generates a clock signal, based on its variable basic cycle time (16, 32, 64, 128, 256 and 512 ms). The Profinet device receives this signal as digital input and provides it on its digital output. The IPC consumes the digital output and counts the received mirrored clock signals. This measurement was done with a LiFi link, see Figure 6 a) and with a wired link, see Figure 6 b). Figure 8 shows the normalized measuring results. A value below 1 indicates information loss; i.e., the information was not always received at the correct point of time. Figure 8 indicates that the behaviour of the LiFi link is more like a cable link with 128 ms basic cycle time or higher.

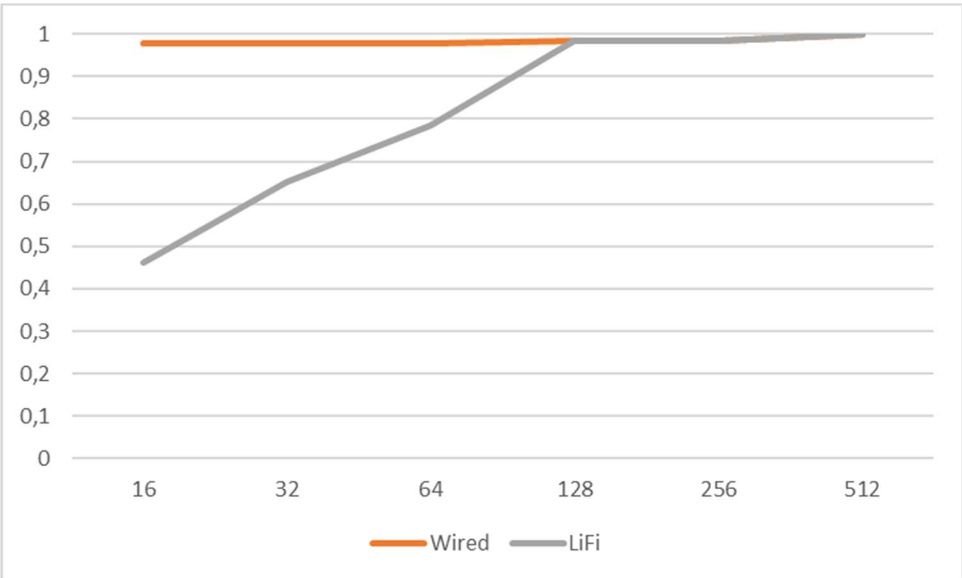

Figure 8 Normalized measurement results for wired and LiFi link for Profinet RT over cycle time in milli seconds

In a second step, in order to assess the handover performance and the performance of the non-3GPP interworking function connecting the 5G / LiFi router to the 5G core, the following three metrics were considered:

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1. Round trip time (RTT),
2. UDP throughput in the up- and downlink direction, and
3. Packet loss as observed during the UDP bandwidth measurement

All metrics were assessed for the link between the 5G/LiFi router (having the measurement point at the position where the HoloLens attaches to the router) and a backend server located behind the 5G core. For the UDP measurements, the imposed traffic load in the downlink direction was set to 500 Mbps, and for the uplink direction to 100 Mbps. Those values correspond to the QoS requirements as previously identified for the industrial use case.

These metrics were evaluated for five experiments. For the first experiment (denoted “console-net” in the following graphs), we assess the performance of the underlying active network components without LiFi or any 5G components in the middle. These results act as a baseline measurement assuring that none of the active network components impose a bottle neck on the set-up.

Also, the performance of the 5G CPE in combination with the used 5G gNodeB is evaluated in an isolated environment (“5G-NR” in the following graphs). This measurement assesses the isolated performance of the 5G SA NR link. In combination with the previous evaluation of the isolated LiFi link, those measurements assure that neither the LiFi nor the underlying 5G radio impose a bottleneck when we add the 5G/LiFi router attaching to the 5G core via the N3IWF function.

The final measurements evaluate the full end-to-end setup involving all components developed with ELIOT: The 5G/LiFi router attaches to the 5G core via the N3IWF over LiFi (“N3IWF-LIFI”) or over 5G NR (“N3IWF-5G-NR”). Those two alternative links are evaluated without causing handovers. Then, in a final step, we interrupt the LiFi link causing a handover of the established connection from LiFi to 5G; and consecutively back to LiFi when the system detects the LiFi link to be up again.

The following figures show the measured KPIs for the five measurement set-ups. 95% confidence intervals are included but are for almost all measurements so small that they are not distinguishable from the plotted data point showing the expected mean of the metric.

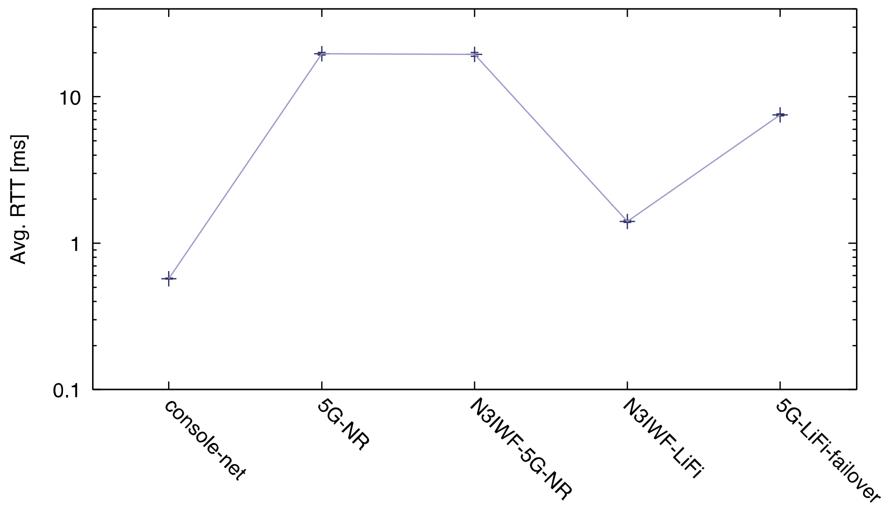

Figure 9 End-to-end round trip times measured in the industrial use case

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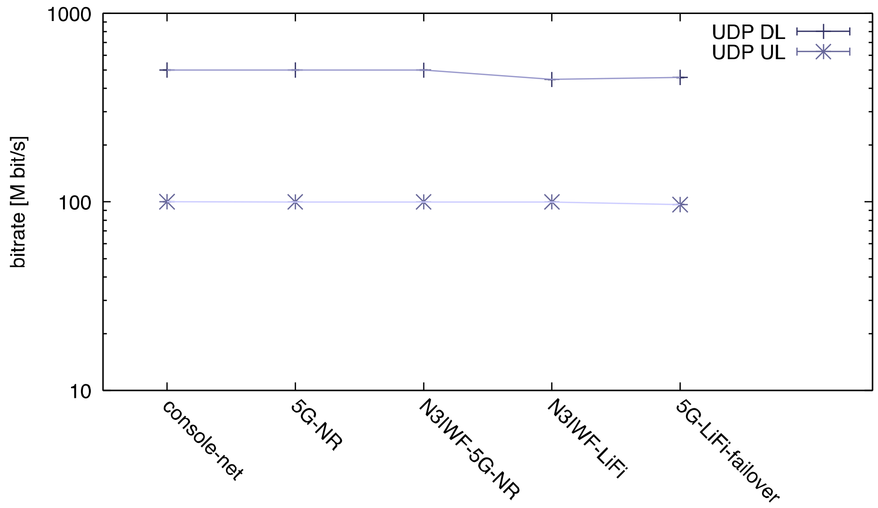

Figure 10 End-to-end packet data rates measured in the industrial use case

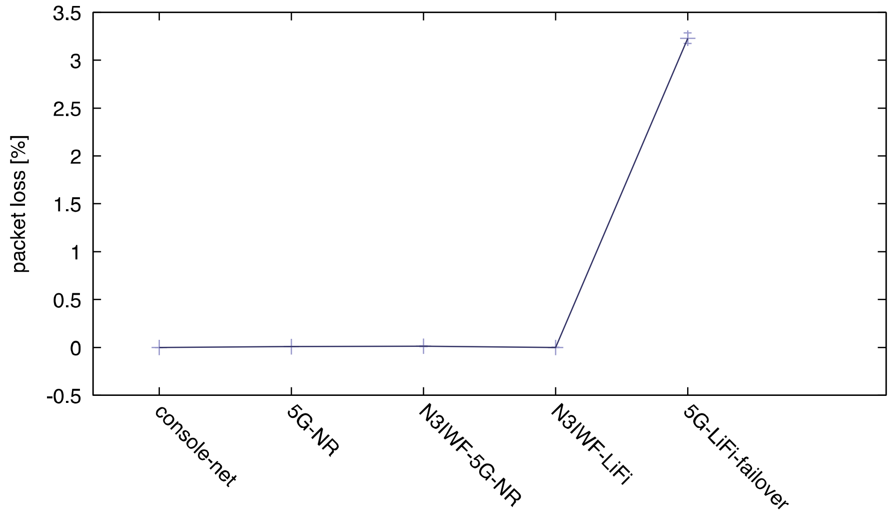

Figure 11 End-to-end packet loss measured in the industrial use case

Looking at the round trip time of 0.5 ms, we can observe that the geographical distribution of the experiment does not impose a bottle neck (“console-net”). The isolated 5G NR link has approximately 11 ms round trip time, which is as expected: the single link delay of a 5G NR link is in the order of 5ms. Adding the N3IWF link establishment over the 5G NR link does not add an observable delay. The confidence interval for both measurements (“5G-NR” and “N3IWF-5G-NR”) overlap. The N3IWF over LiFi connection has a significant lower delay of approx. 1.2 ms. This corresponds to the expected behaviour of the LiFi modems acting as a transparent Ethernet bridge, which immediately forwards incoming packets. Finally, the delay for the experiments involving handover between 5G and LiFi is in

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the order of 8ms, which is – as expected – in between the 5G NR and LiFi performance as packets are, depending on the link availability, forwarded via 5G or LiFi.

Regarding the bitrates, all experiments fulfil the use case requirement demanding 500 Mbps in the downlink and 100 Mbps in the uplink. The demanded bitrate is even maintained while conducting handover between 5G and LiFi; the number of dropped packets during a handover is so small that the packet loss does not significantly affects the bitrate.

This observation corresponds with the observed packet loss. Without handover, the packet loss for all experiments is zero. When a handover occurs, we observe approx. 3.2% packet loss. This is mainly caused by implementation implications of attaching LiFi to the 5G/LiFi router. The LiFi modems are attached via an Ethernet cable to the 5G/LiFi router. Thus, even if the LiFi link is interrupted (aka. “down”), the 5G/LiFi router observes a working Ethernet interface towards the LiFi modem as the Ethernet link between the router and the LiFi modem is always “up”. This, the LiFi-down event can only be observed by detecting lost packets of a continuous in-band-probing of the end-to-end link. This effect can be overcome in future implementations of the LiFi link, in which the link is natively, i.e., via a system driver, attached to the router; this would also allow LiFi to actively signal a link-down event to the router further improving the handover performance.

1.5. Conclusions Industrial Communications

The demonstrator setup at Fraunhofer HHI shows that the vertical handover between LiFi and 5G works well using the non-3GPP Inter-Working Function (N3IWF). However, a 5G / LiFi Router NAT Gateway was used to realize the demonstration because there is currently no native LiFi/5G chip set available on the market. For such use cases, it is essential that mobile devices are equipped in the future with integrated communication modules (chip sets) that support native LiFi and 5G, so that the vertical handover can be realized by the chip set. Performance evaluations show that the prototype set-up implemented in ELIOT meets the link requirements for the industrial use case.

The demonstrator setup at Weidmüller shows that LiFi generally supports OPC UA and Profinet, but we have found that the LiFi modules cannot guarantee real-time data transfer at cycles times lower than 128 ms. Moreover, we have found that the LiFi modules (chip sets) used are not compatible with all embedded systems and remote I/O fieldbus couplers tested. Hence, the setup for testing industry protocols was realized using a notebook for Host B; i.e., the Profinet device was realized in software and not fully in hardware (ASIC). Therefore, further work is needed on the LiFi modules (chip sets) for optimizing them for real-time data transfer and for collaboration with industrial embedded systems and remote I/O fieldbus couplers.

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2. Industry Positioning Demonstrator

2.1. Motivation for LiFi based positioning

Localization services besides reliable wireless communications are essential enablers for smart manufacturing. Tools and robots are connected via wireless links to a local cloud in which the information from numerous sensors and actuators are collectively processed in order to control the entire work flow. The purpose is to react in real-time to situations and events, ideally in a proactive manner, based on a previously learned set of methods. For identifying the most appropriate method from a large data base of previously learned ones, it is essential to know the position of the tools or robots, as otherwise, the search space might be too large and it is hard to make decisions in real-time.

Positioning or localization in industrial environments enables modern industrial applications to support the evolution of smart factories by determine the position of mobile devices including intelligent transport systems (ITS), smartphones, tablets as well as (semi-) finished products, and other production resources that are needed in the factory.

Figure 12 shows a factory transport system of the ELIOT partner Weidmüller. It transports parts on pallets following predefined, which is also referred to as automated guided vehicle (AGV). The transport system prohibits crashes which can happen due to obstacles, however, it is not able to determine a new path on-demand since deviation from pre-defined paths are not possible. The desired manner is to provide flexible movements to prevent blockages. By equipping AGVs, with positioning functionalities, they are no longer limited to the fixed route defined with the optical markers.

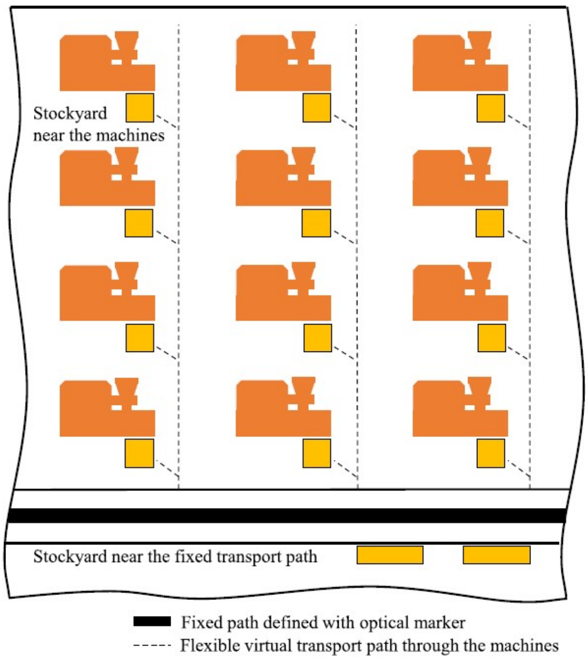

Figure 12 AGV transport system with flexible paths

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The transport system will navigate through the machines along the dashed lines. These dashed lines represent virtual routes that are defined by position coordinates used for navigation. The transport system can drive directly to a stockyard of a machine. In this scenario, the path, the source, and the target positions can be defined and changed in a "transport system navigation software" when machines are transposed. This makes the production more flexible and scalable, which helps to increase productivity. Potential optimization in productivity identifies through value stream management and reorganization.

Optical wireless communications (OWC), is a promising candidate to complement radio frequency (RF) wireless systems in indoor environments such as factories. OWC systems use light as a medium for mobile communications. OWC can be easily combined with, and has similar deployment like illumination. In all illuminated areas, communication is possible, too. OWC access points use the conventional power lines or Power-over-Ethernet as a fixed backbone. Such networked OWC systems are denoted as light fidelity (LiFi). LiFi systems operate in unlicensed optical spectrum. LiFi is robust against electromagnetic interference (EMI). Moreover, as light does not penetrate through walls, communication is limited to one room. For the same reason, LiFi cannot be jammed by RF systems and it provides additional security in this way. Finally, propagation of LiFi is mainly based on the line-of-sight. Reflections are diffuse and not specular as in most RF systems. Thus, multi-path propagation plays a negligible role. Because of its obvious advantages, it is nearby to consider LiFi also for positioning and to integrate it with wireless communications.

2.2. Scope of the demonstrator

The positioning demonstrator in ELIoT shows the feasibility of LiFi-based positioning in an industrial environment. The positioning system is complementary to a standard LiFi communication system and does not require additional hardware. The used LiFi frontends are capable to transmit up to 1 Gb/s and allow positioning at the same time. The demonstrator shows two aspects. First, the position of an object inside the LiFi cell is estimated at cm accuracy and second, the movement of the object is tracked.

Due today's lack of the certain features available in the current LiFi chip sets, it is not possible to have a real-time LiFi positioning system like for the other demonstrations. Therefore, only a semi-live system is demonstrated, which allows only a limited update rate of the object position. The demonstration itself was set up at Weidmüllers factory. Target key performance indicators of the demonstrator are cm accuracy, a coverage area of about 5 m^2 with at least 6 OFEs and eye safe conditions.

The LiFi positioning demonstrator is the results of numerous analytical, simulative and experimental investigations, which took place during the project duration. The main findings have been published in:

- V. Jungnickel et al., "Enhance Lighting for the Internet of Things," 2019 Global LIFI Congress (GLC), 2019, pp. 1-6, doi: 10.1109/GLC.2019.8864126.
- V. Jungnickel et al., "LiFi for Industrial Wireless Applications," 2020 Optical Fiber Communications Conference and Exhibition (OFC), 2020, pp. 1-3.

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- J. P. Linnartz et al., "ELIoT: New Features in LiFi for Next-Generation IoT," 2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), 2021, pp. 148-153, doi: 10.1109/EuCNC/6GSummit51104.2021.9482478.
- K. L. Bober et al., "Distributed Multiuser MIMO for LiFi in Industrial Wireless Applications," J. Lightwave Technol. 39, 3420-3433 (2021)
- S. M. Kouhini et al., "LiFi Positioning for Industry 4.0," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 27, no. 6, pp. 1-15, Nov.-Dec. 2021, Art no. 7701215, doi: 10.1109/JSTQE.2021.3095364.
- S. M. Kouhini, Z. Ma, C. Kottke, S. M. Mana, R. Freund and V. Jungnickel, "LiFi based Positioning for Indoor Scenarios," 2021 17th International Symposium on Wireless Communication Systems (ISWCS), 2021, pp. 1-5, doi: 10.1109/ISWCS49558.2021.9562207.
- Z. Ma et al. "LiFi Positioning and Optimization in an Indoor Factory Environment," 48th Annual Conference of the IEEE Industrial Electronics Society (IECON), 2022 *(submitted)*
- S. M. Kouhini, "Object Tracking in an Indoor Scenario: Potential for Centimeter Accuracy with LiFi," 13th IEEE/IET International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), 2022 *(submitted)*

Furthermore, a video showing the demonstration at the Weidmüller factory is available at the ELIOT website (https://www.eliot-h2020.eu/).

2.3. Demonstrator setup

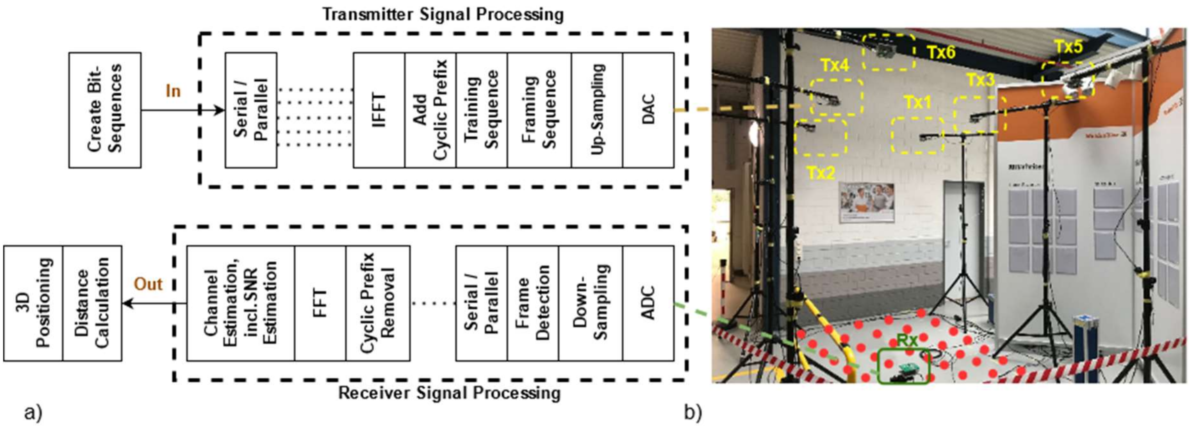

Figure 13 Block diagram of transmitter and receiver signal processing for the proposed LiFi positioning system. b) Measurements setup in the factory hall. Red dots show measurement points

The experiment was performed at Weidmueller's factory as presented in the Figure 13(b). The location was inside the hallway between two machine shop floors, where typically AGV move around to transport materials. Two neighbouring LiFi cells have been set up, with 6 ceiling units placed in a rectangular plane with around 1.5 m distance, covering around 4.5 m^2. The actual positions of the ceiling units have been initially estimated with a laser range meter. Within the coverage area, we defined 35 points for evaluating the position estimation of the mobile unit. Before starting the actual system evaluation, a calibration was performed at two points in the area, to estimate the additional delay due to the cables, devices and optical frontends. The 6 ceiling units consisted of a custom-designed LED drivers with the off-the-shelf LEDs and the mobile unit consisted of 5 parallel driven large-area silicon photo-diodes.

The digital signal processing of the positioning demonstrator is based on ITU-T G.9991 standard. We used dedicated pilot signals to estimate the channel from each ceiling unit to the mobile unit, from which the distance can be calculated. This allows us to get the actual 3D position of the mobile unit, when we combine the know positions of the ceiling units with the distance information. Furthermore, an optimization approach based on the relation of the propagation angle of the LED and transmission delay has been introduced to improve the accuracy.

2.4. Measurement results

The demonstrator was evaluated by comparing the actual positions of the mobile unit, measured with a laser range meter, with the position estimated using the LiFi system. In Figure 14(a-c) the heat map for the x,y,z error is shown, which is defined by the root mean square error (RMSE) between the actual und the estimated position for each dimension. The performance slightly varies in the different section of the LiFi cell. The X direction shows higher errors in the middle of the cell, while Y and Z direction show high errors in the top left corner. The small areas with very high errors (>15 cm) can be attributed to poor SNR conditions at these points. The overall RMSEs for X,Y and Z direction are 7 cm, 6 cm and 3 cm as shown in Table I.

Table 1 Position accuracy with and w/o optimization

	x-axis	Y-axis (m)	Z-axis (m)	Mean RMSE (m)
Regular Measurement	0.07	0.06	0.03	0.053
Optimized Measurement	0.05	0.04	0.01	0.033

In Figure 14(d-f) the performance with the optimization approach is shown. The accuracies improve for all dimensions and the areas with very high errors, e.g., at the top left corner for Y and Z and the middle left area for X direction, could be minimized as well. In Table I the RMSE in the X, Y and Z-directions and the total mean RMSE before and after the optimization are shown. The RMSE for each direction could be reduced by about 2 cm, down to 5, 4 and 1 cm in X,Y and Z direction, respectively. The mean RMSE over all three direction could be reduced from 5.3 down to 3.3 cm.

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

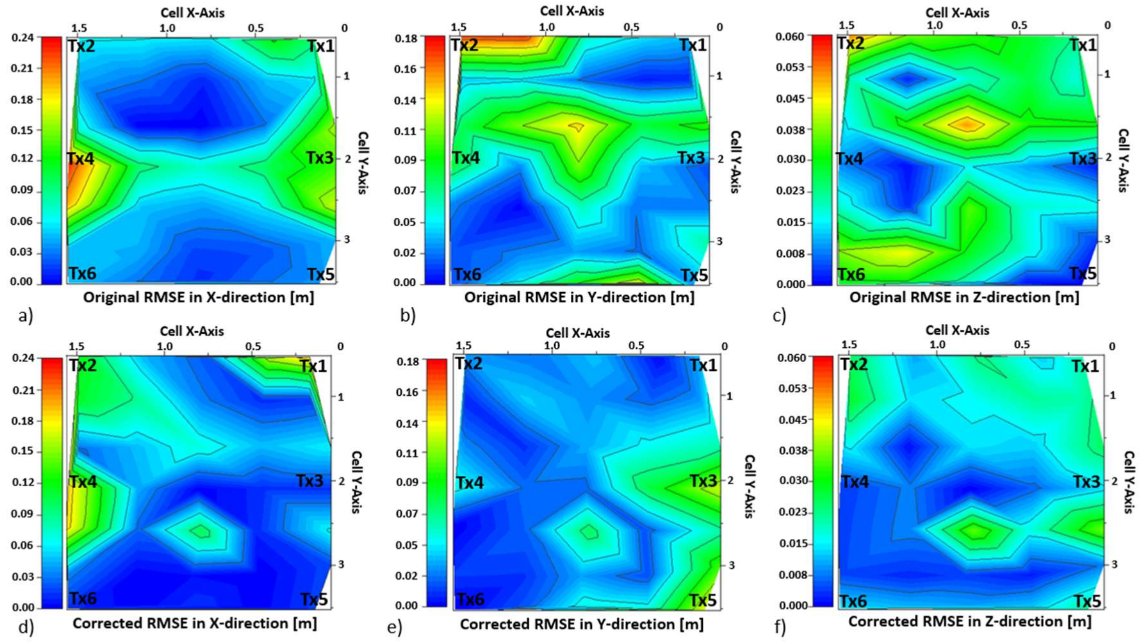

Figure 14 (a-c) Regular RMSE in X,Y and Z-direction. (d-e) Optimized RMSE in each X,Y and Z-direction.

A more detailed analysis of the results is given at the IECON 2022 workshop on Lifi for industrial applications.

A further test involved the tracking of a moving object inside a LiFi cell. Figure 15 illustrates the measured location of an object that was moved to a number of locations and successfully tracked with the system as shown by the circles. Due to the relative low data processing speed of DAC and ADC, only 1 measurement / second could be realized, which limits the mobility. Real-time implementation of Field Programmed Gate Arrays (FPGA) is the task of future developments.

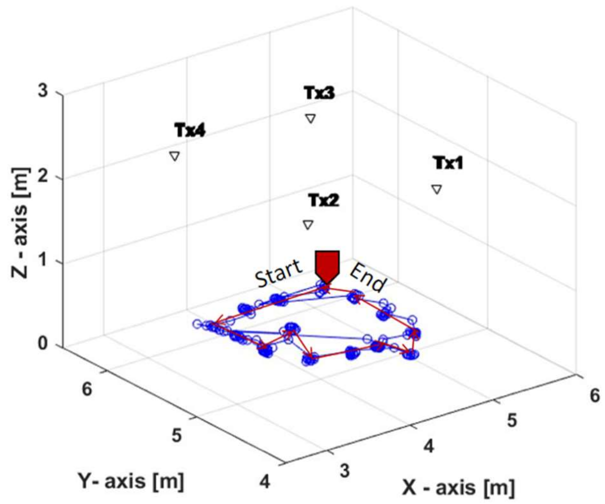

Figure 15 Tracking of a moving object inside a LiFi cell.

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2.5. Conclusions Positioning

The ELIOT LiFi positioning demonstrator shows the feasibility and high performance of optical wireless-based localization in an industrial environment. The localization approach is directly based on the ITU-T G.9991 standard for optical wireless communication, which means that the same system can be used for communication and positioning. The results demonstrate an average accuracy of about 5 cm, which can be improved to only 3 cm by introducing an optimization approach. Furthermore, an active tracking of a moving object was successfully demonstrated.

The ELIoT positioning demonstrator has met the project objective to develop a profound system concept for integrating LiFi into IoT for positioning and broadband data. The shown performance corresponds to the needs of high precision positioning in an industrial environment. Standardization activities in IEEE and ITU-T to bring LiFi-based positioning in the market are ongoing and allow the integration of positioning into the next generation of LiFi chipsets.

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