Enhance Lighting for the Internet of Things

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Office LiFi Demonstrator

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Partners contributed	SIG, TU/e, MXL

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Abstract

This document reports on the ELIOT demonstrator for LiFi in Office use cases. This demonstrator intends to show capabilities of LiFi in serving communications needs of typical office environments. With growing bandwidth requirements of modern applications, such as video conferencing, LiFi can play a significant role especially in densely occupied offices. In such settings, the LiFi network can augment congested WiFi networks.

The high-level objectives of the office demonstrator are summarized as follows:

1) Bust the myth "LiFi will fail in the market as it is not robust to blocking a light beam".
2) Understand what a 2nd-generation ITU g.vlc standard needs to have.
3) Explore options for reducing cost and power consumption, e.g., cheaper fronthaul.
4) Investigate wavelength division multiplexing (WDM)-over-POF fronthaul with improved electromagnetic interference (EMI) susceptibility.

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Index of terms

ITU	International Telecommunication Union
PHY	Physical Layer
DLL	Data Link Layer
LEDs	Light-Emitting Diodes
OFDM	Orthogonal Frequency-Division Multiplexing
MIMO	Multiple-Input Multiple-Output
QAM	Quadrature Amplitude Modulation
SISO	Single-Input Single-Output
OFEs	Optical Frontends
PLC	Power Line Communication
POF	Plastic Optical Fiber
SNR	Signal-to-Noise Ratio
LoS	Line-Of-Sight
WDM	Wavelength Division Multiplexing
D-MIMO	Distributed MIMO
LD	Laser Diode
MUX	Multiplexer
DMX	Demultiplexer
PD	Photodiode
TIA	Transimpedance Amplifier
TU/e	Eindhoven University of Technology
EMI	Electromagnetic Interference

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Content

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1. Introduction

Currently, data needs of office environments are mainly served by WiFi. There is a trend for increasing data traffic due to increasing multimedia usage for video conferencing and cloud-based services for data backup. This is further exasperated when the occupant density increases. LiFi has the potential to alleviate the stress on WiFi networks by providing an alternative communication path via optical wireless communication.

The office LiFi demonstrator is based on the International Telecommunication Union (ITU) G.9991 standard, also known as G.vlc. The standard specifies the system architecture, physical layer (PHY) and data link layer (DLL) for high-speed visible and infrared light communication. The G.vlc standard is a derivative of the recommendation G.hn (G.9960) which provides a high-speed backbone for both LiFi and WiFi applications. G.vlc defines important features for dealing with the band–limited and low–pass response of commonly used light sources for LiFi systems, such as the light-emitting diodes (LED). These features include orthogonal frequency-division multiplexing (OFDM), adaptative bit-loading, multiple-input multiple-output (MIMO), M-ary quadrature amplitude modulation (QAM) and others.

To accelerate mass market adoption of LiFi systems, a range of solutions make use of the already available G.hn chipsets. As described [1], the chipsets available in the market can provide high-speed networking solutions for different wired mediums such as, power cables, phone lines, coaxial cables and POFs. The achievable physical data rates are up to 1.7 Gbps over both phone line and over coaxial cable, and up to 1 Gbps over powerline. They have support for single-input single-output (SISO) transmission with 200 MHz bandwidth on phone lines or on coaxial cables and MIMO transmission with 100 MHz bandwidth on phone line or on power line profiles. In this demonstrator, the performance of LiFi systems is investigated using G.hn chipsets with powerline and phone line profiles under different link conditions.

With respect to LiFi, a typical office room is partitioned in coverage regions which are served by multiple optical frontends (OFEs). The OFEs are grouped together and connected to one of the two MIMO channels via a splitter-combiner block. Figure 1 shows a high-level architecture of the office demonstrator based on a modified power line communication (PLC)-MIMO modem. A mobile terminal, also based on a modified PLC-MIMO modem, if used to interface the user device (e.g., laptop) to the LiFi network.

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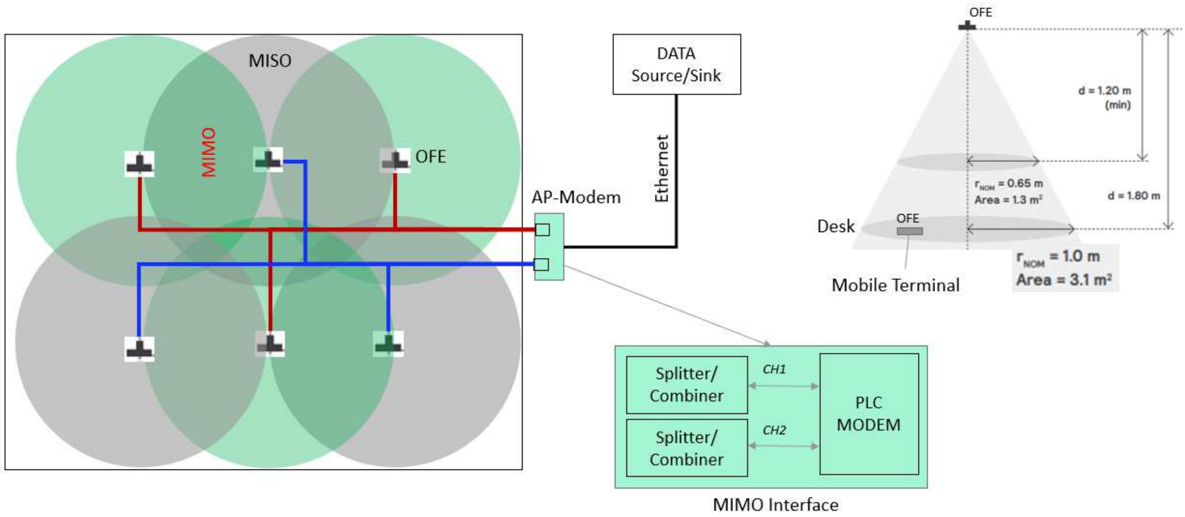

Figure 1: Architecture of office demonstrator.

Both CAT5 copper cable and plastic optical fiber (POF) fronthaul technologies are candidates for connecting the OFEs to the modem. The MIMO functionality is available in the overlap regions where the mobile terminal can be served by two ceiling OFEs connected to different MIMO channels. The size of the coverage area depends on the spacing between the OFEs, the height of the transceiver from the desk and the opening angles of the OFEs on the ceiling and the mobile terminal. The wider the overlap region, the more robust the LiFi link becomes for line-of-site link interruption.

2. Scope of the demonstrator

The scope of this work is to demonstrate a reliable wireless optical network for office applications which can deliver around 100 Mb/s throughput while providing robustness against partial loss of line-of-site link by using MIMO technology.

The demonstrator consists of a ceiling unit built from six Trulifi optical frontends [2] that are connected to a PLC-MIMO modem [1]. The two transmit/receive channels of the MIMO modem are further expanded into 3 TX/RX channels using signal splitters and combiners. Together with a 24V power, the signals are connected to the six OFEs using CAT5 cables. The ceiling units communicate with a mobile terminal built from two optical frontends that are connected to a PLC-MIMO modem.

The demonstrator is used to evaluate how well a PLC modem, which has been developed for a less dynamic communication channels, can cope with mobility which is typical to office use case. Since user mobility will affect the LiFi communication channel, the learnings from the demonstrator will generate inputs for next-generation G.vlc standard.

3. Office LiFi MIMO based on PLC G.HN modem (Signify Office)

3.1. LiFi - MIMO based on a PLC G.HN modem

Figure 2 shows a photo of the PLC-MIMO demonstration setup. The ceiling consists of six OFEs mounted on an acoustic tile. The spacing between the OFEs is chosen to have reasonable overlap

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regions when MIMO functionality is available. The OFEs are connected to the PLC-modem by six CT5 cables which also carry power for the electronics. The distance between the ceiling and the mobile device is ~1.8 m.

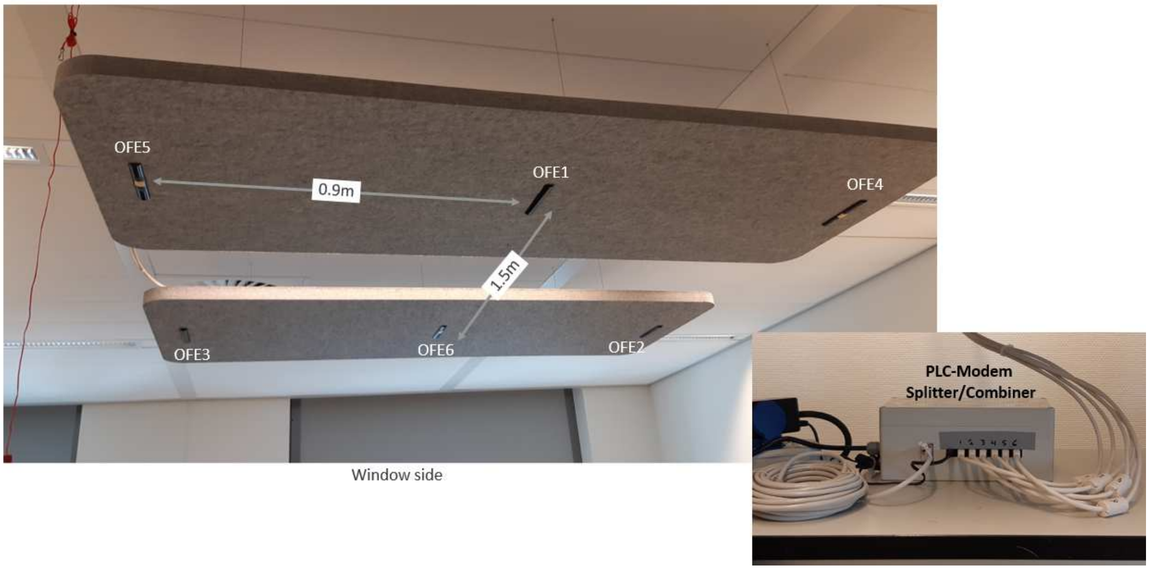

Figure 2: Office demonstrator: ceiling LIFI-MIMO installation

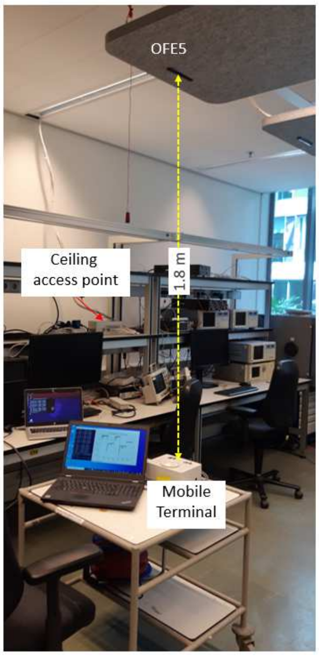

Figure 3: LiFi-MIMO demonstrator test setup. Two laptops are used as data source and sink to evaluate the link performance using iPerf and Spirit Configuration tools.

Internal details of the ceiling access point and the mobile device are shown in Figure 4. Each transmit channel of the ceiling PLC modem is split into three TX channels that are fed to respective OFEs via

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CAT5 cables. Received signals from three OFEs are combined into to one signal that is input to one of the two MIMO RX channels. On the mobile unit side, each PLC MIMO channel is connected to a single optical frontend. The received optical signals are boosted using trans-impedance amplifiers to match the PLC modem input requirement.

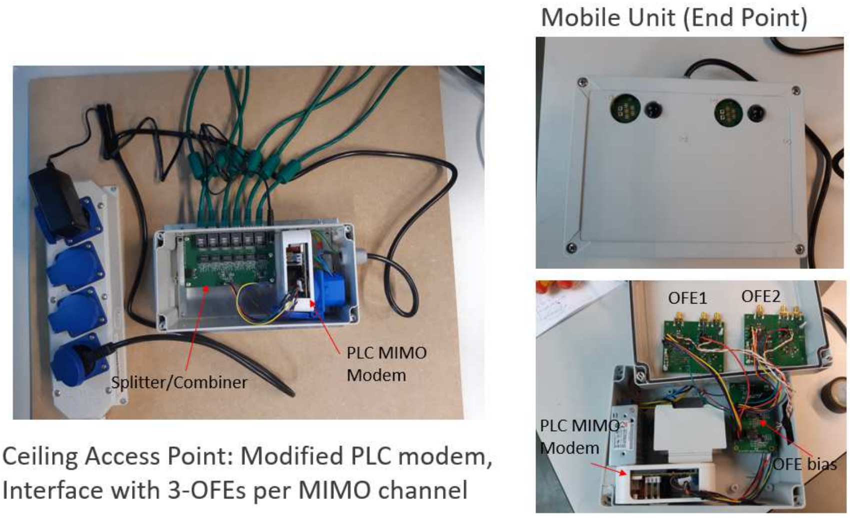

Figure 4: Office demonstrator components.

3.2. Measurement results

3.2.1. LiFi - MIMO throughput

Downlink and uplink throughput were measured using iPerf and a software called as “Spirit Configurator tool” from MaxLinear. Net and raw data throughput measured at various locations in the room are shown in Figure 5 for the downlink and Figure 6 for the uplink. While raw throughput can reach up to 150 Mb/s, net data rate ranges from 70 – 89 Mb/s. Regions where signals from two OFEs overlap show improved throughput due to improved signal-to-noise ratio (SNR). Although the uplink performance is slightly lower, measured throughput is still good enough for office applications. In practice, the total capacity needs to be shared among multiple users occupying the same area covered by a single ceiling access point.

OFE2 76/(78,127)	77/(79,134)	OFE6 78/(82,133)	76/(80,130)	OFE3 73/(75,126)
77/(85,138)	89/(92,152)	87/(90,152)	89/(94,153)	79/(80,133)
OFE4 73/(77,127)	87/(92/152)	OFE1 85/(87/149)	86/(90/149)	OFE5 74/(77,125)

Figure 5: Downlink throughput [Mbps]: measured by iPerf (net) / Spirit(net, raw).

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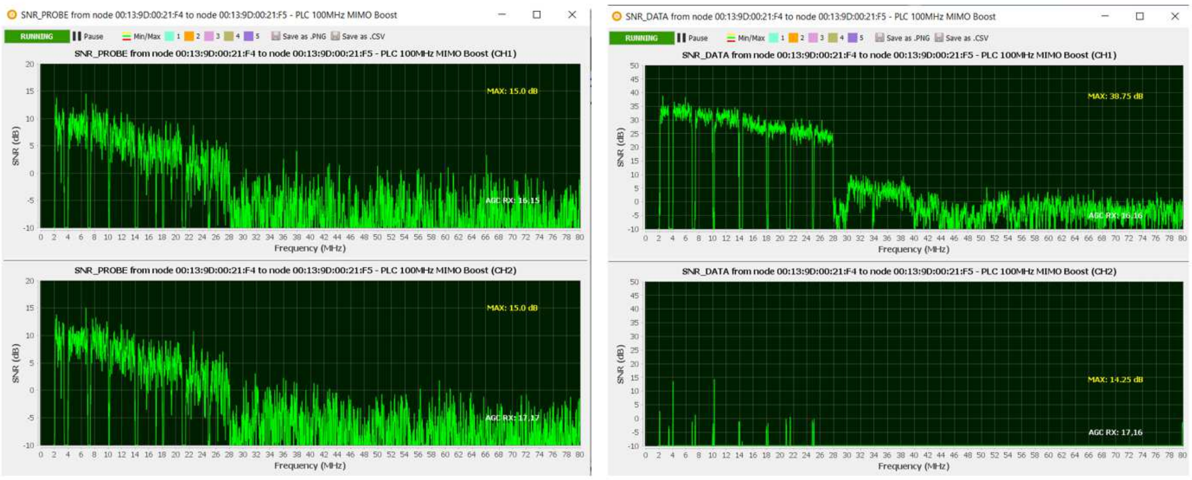
OFE2 64/(67,117)	70/(73,129)	OFE6 68/(70,125)	75/(79,142)	OFE3 73/(77,138)
67/(69,122)	71/(73,130)	72/(74,130)	78/(81,146)	80/(84,151)
OFE4 64/(66,117)	67/(71,124)	OFE1 69/(72,127)	80/(82,147)	OFE5 66/(69,123)

Figure 6: Uplink throughput [Mbps]: measured by iPerf/Spirit (net, raw).

The throughput limitation is attributed to three factors (i) use of PLC modem technology which limits the usable spectral band due to regulations on notches and power spectral density (PSD) above 30 MHz (ii) limited transmit optical power for eye safety and wider coverage area (iii) non-ideal MIMO signal processing which considers part of the received signal as interference that leads to degradation in SNR. Limitations due the choice of a PLC modem can be addressed in future G.vlc standards by increasing PSD above 30 MHz.

3.2.2. Impact of partial line-of-site blockage

To demonstrate robustness against LoS blockage, tests were conducted by covering one of the OFEs of the mobile unit. Figure 7 shows SNR snapshots of the MIMO channels: (A) without line-of-sight blockage and (B) with partial blockage. The measurement was taken when the mobile terminal was placed between OFE2 and OFE6. Impact of covering one of the OFEs is visible on the right bottom plot where the SNR of one MIMO channel is very low.



(A) No line-of-site blockage: 86 Mbps net throughput

(B) One line-of-sight blocked: 79 Mbps net throughput

Figure 7: Signal-to-noise ratio (SNR) plot of downlink without and with line-of-site blockage and respective net throughput.

One important aspect of communication systems is their speed of adaptation to changes in channel characteristics. When the line-of-sight (LoS) is blocked or un-blocked, the PLC MIMO modem adapts its operation to cope with the changes. Figure 8 shows the downlink and uplink throughput when blocking and unblocking the OFEs of the mobile device. The communication system stays operational, with reduced throughput, when one of the channels is blocked. The PLC modems require a few seconds to identify the channel change and adapt their communication parameters accordingly. Slow

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performance is to be anticipated as the modems were originally developed for a slowly changing wired communication channel. Updates in future G.vlc standards can resolve this issue.

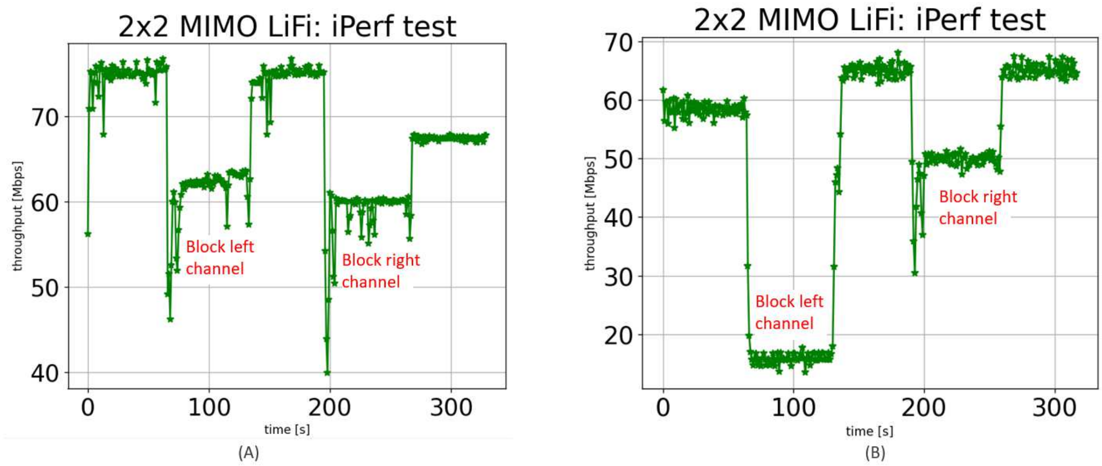

Figure 8: Impact of partial line-of-sight blockage when mobile device was placed under ceiling OFE5: (A) downlink, (B) uplink

3.2.3. Impact of mobility

Tests were also conducted to verify the system performance while moving the user device slowly in the demo area. Figure 9 shows downlink an uplink throughput performance. While some of the regions show net performance reaching 80 Mbps, there are also transition areas where the throughput drops for few seconds. This is caused by the varying SNR in the coverage area, availability of MIMO where signals from two or more OFEs are available and the response speed of the modems to the channel changes.

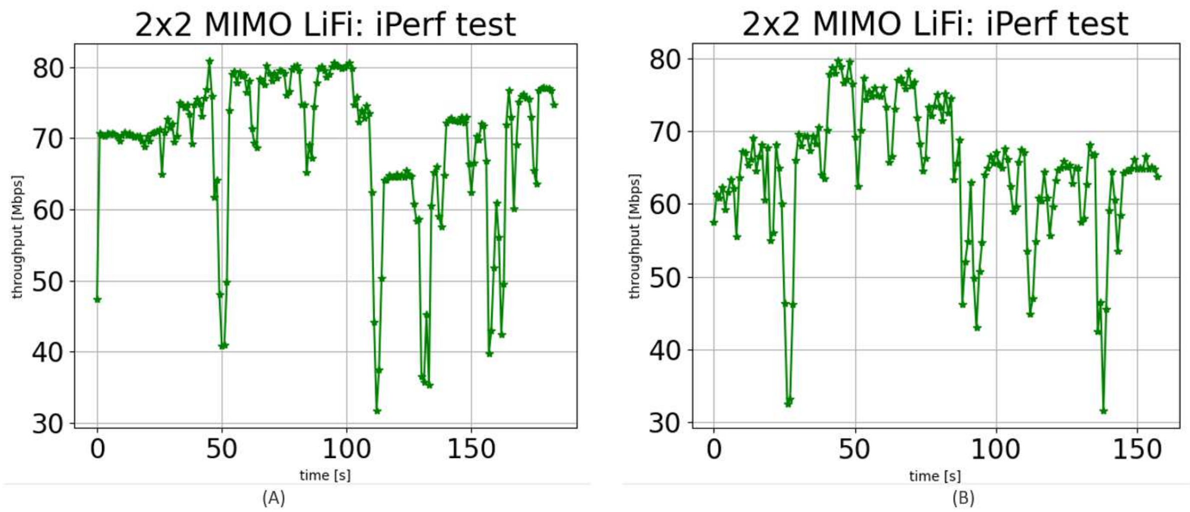

Figure 9: Impact of mobility on throughput: (A) downlink. (B) uplink.

4. WDM-POF next-generation fronthaul setup (TU/e Office)

In a second part of this demonstrator, we evaluate the bidirectional performance (downlink and uplink) of a LiFi system in a typical office room where the fronthaul is composed of wavelength division multiplexing (WDM)-over-POF. The setup intends to demonstrate the use of a transparent optical

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solution for fronthaul for LiFi luminaires. In ELIoT, we chose to adopt a WDM solution over large-core (1mm core diameter) step-index POFs. POFs are an attractive solution for indoor communication networks due to its low cost, small bending radius, and do-it-yourself capability. Another advantage of this standard POF is that it works in the visible wavelength range, which eases the installation and inspection because it allows visual link testing. Moreover, POFs have immunity to electromagnetic interference, which means that they can go through the same duct of electrical power installations. A disadvantage of POF fronthaul in comparison with CAT5 copper fronthaul is that extra power supplies are required to power the POF transceivers and LiFi OFEs. In the CAT5 case, 24V DC power and signals can go together through the same cable.

For this demo, two light sources emitting in different wavelengths are used to send/receive signals from two ceiling luminaires of the POF. The overall system is composed of a phoneline evaluation Kit from MaxLinear, a WDM over POF fronthaul, a distributed MIMO (D-MIMO) LiFi link and a client device. In the downlink channel, at the transmitter side, the Eval kit board feeds electrical signals into the POF fronthaul. The electrical signal injected by the Eval kit is converted to optical by two independent light sources, a red LED and a green laser diode (LD). The optical signal from both red and green wavelengths are combined within a multiplexer (MUX) device, which is shown in Figure 16. The combined light goes then through a POF cable and, at the end of the link, the signal is separated back to two independent colours by a demultiplexer (DMX) device. Each one of the colours feeds a LiFi OFE installed in the ceiling. Before going into the LiFi OFE, the optical signal is converted back to electrical by an optical receiver, composed of a photodiode (PD) and a transimpedance amplifier (TIA). Subsequently, the amplified signal feeds an LED which is inside the OFE. The output optical signal from the LiFi OFE is then transmitted through the free-space channel to the optical receiver of the client device. Data sent by the evaluation kit installed in the ceiling is then recovered by another evaluation kit board connected to the client device.

In the uplink channel, the evaluation kit board is connected to two LiFi OFEs, which are closely placed in a way to simulate a LiFi user device. The transmitted electrical signal by client device equipment is converted to optical by the LEDs. Then, the optical signal goes through the free-space channel and is converted to electrical domain by the photodiodes in the ceiling OFEs. The electrical signal is amplified and then feed to red and green LEDs, the output of which are combined by an optical MUX and applied to the POF cable. At the end of the POF link, the optical signals are separated by an optical DMX unit. Each output optical signal from the DMX is converted back to electrical by a PD and amplified again before going to the Eval Kit board. At the end, the transmitted data by the client device is recovered by the Eval Kit board. Both downlink and uplink channels from the concatenation between WDM over POF and D-MIMO LiFi are depicted in Figure 10. The distances d_1, d_2 and d_3 corresponds to, respectively, distance between LiFi user device and ceiling infrastructure, distance between OFEs installed in the ceiling, and measured coverage area.

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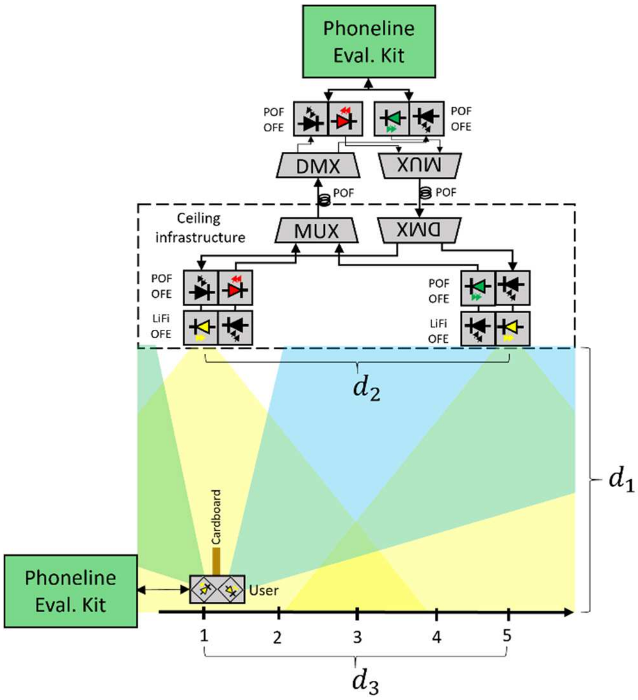

Figure 10 Illustration of the WDM over POF fronthaul used to feed signals to a 2x2 MIMO D-MIMO LiFi communication system.

4.1. Demonstration Setup

Figure 11 shows a 2x2 D-MIMO LiFi optical demonstrator setup installed in a typical office room. The LiFi wireless channel is composed by four Trulifi optical frontends [2]. Two of them are installed in the ceiling, 1m away from each other and, two others are placed above a table closely placed together simulating a LiFi user device. The user device LiFi equipment is shown in Figure 12. The distance between the ceiling infrastructure and the LiFi user terminal is approximately ≈1.8 m. The OFEs in the ceiling are connected to a WDM-over-POF fronthaul, which works as a transparent optical solution to transport the transmitted and received signals from and to the LiFi access point.

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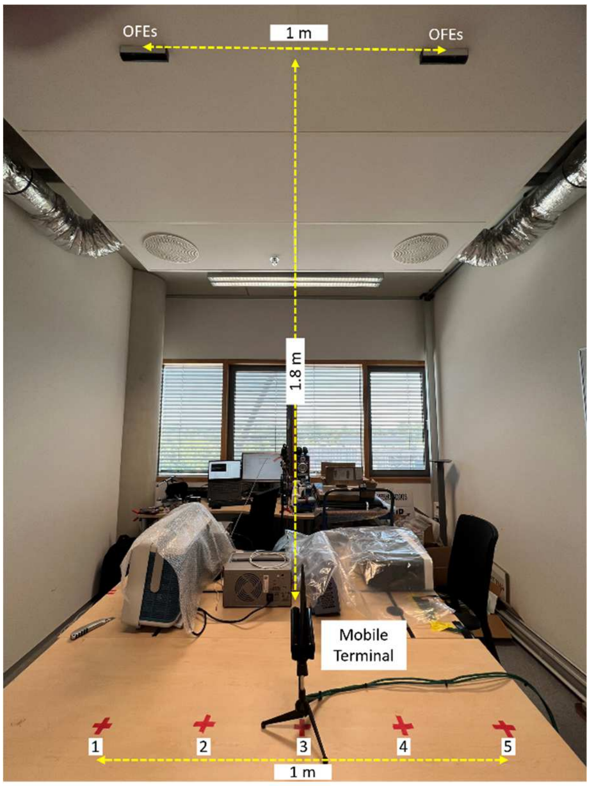

Figure 11 Office demonstrator: WDM fronthaul feeding 2x2 D-MIMO LiFi.

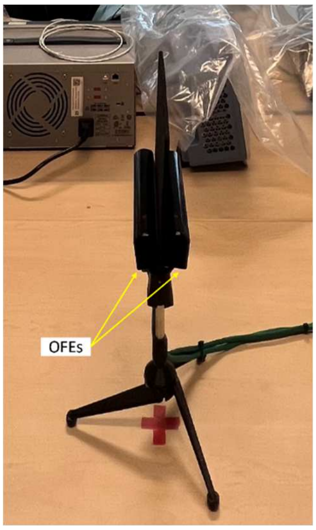

Figure 12 LiFi user device.

4.1.1. POF fronthaul

The POF fronthaul is composed of four POF transceivers, two MUXs, two DMXs and POF cables. As illustrated in Figure 10, in this demonstrator we considered light sources emitting at two different wavelengths, 515 nm and 650 nm, i.e., green and red colors, respectively. Thus, two POF transceivers have a red LED in their electronic circuits and the two others have a green laser diode. The green light POF transceiver is shown in Figure 13 (a). It is a small device, of around 5 cm x 5 cm x 4 cm (length x width x height), which contains all the electronics required to transmit and receive signals from a signal

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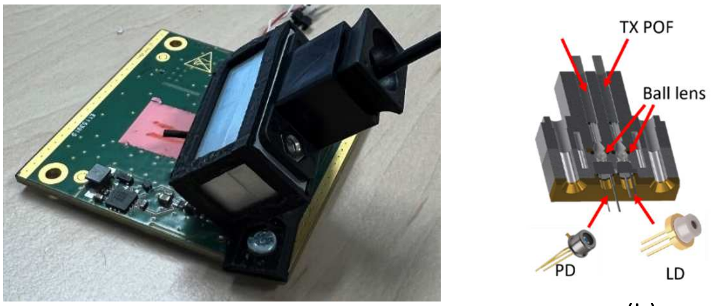
processing chipset to a POF cable, such as a green LD, a PD, a TIA, and power connections. A special aluminium package was designed at Eindhoven University of Technology (TU/e) to hold both the LD and the PD together in a small packaging. In addition, the aluminium material relieves temperature from the LD, working also as a small heat-sink, and the packaging is designed to provide quick and easy POF connection, as shown in Figure 13 (b).



(a) (b)

Figure 13 (a) Green color POF transceiver composed by a green laser diode, a photodiode and electronics on a PCB. (b) POF transceiver package designed at TU/e.

The red POF transceiver is shown in Figure 14. The electronics on the PCB are the same as on the PCB of the green POF transceiver with the difference that the red LED and PD package is a commercially available RC-LED package (Firecomms FB00AKAR) as shown in Figure 14.

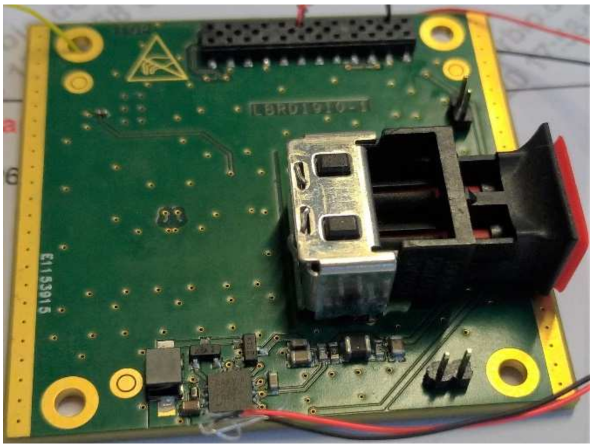


Figure 14 Red color POF transceiver composed by a red RC-LED, photodiode and electronics on a PCB.

To implement the WDM-over-POF, a MUX/DMX is needed. Among the different approaches for implementing the DMX, we focus here on the approach based on 0-degree incidence dichroic filter because it is compact. It can easily be mounted on the ceiling, has low losses and low crosstalk. In Figure 15, architecture of this DMX unit is presented. The two ball lenses are placed in the front and back focal points to provide better coupling from and to the fibres. A WDM filter, with cut-on wavelength at 605 nm, is inserted between the two ball lenses. The WDM filter has a coating that allows the higher wavelength (658 nm - red) to be transmitted and the lower (405 nm - blue or 520 nm - green) to be reflected. The manufactured prototype, shown in Figure 16, is compact (≈11 cm long) and can be used as MUX and DMX. The DMX is mainly characterized by measuring the crosstalk and losses provided by each wavelength. For the developed prototype, a loss of 3.4 dB and crosstalk

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of -13 dB are measured for the green channel. For the red channel, a loss of 4 dB and crosstalk of -25 dB are measured.

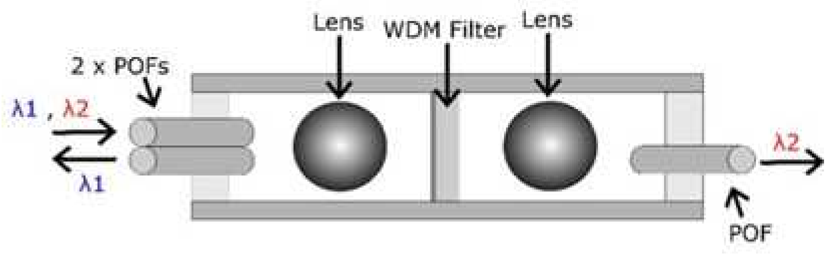

Figure 15 MUX/DMX structure.

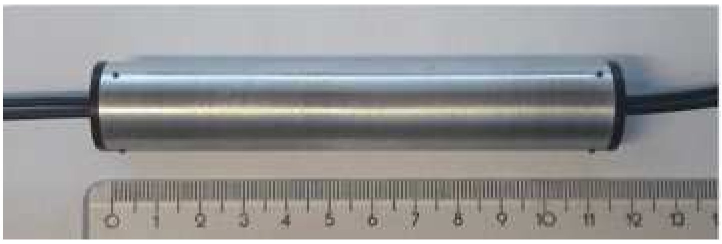

Figure 16 MUX/DMX device.

Note that the optical MUX and DMX components are not off-the-shelf components yet. They were designed and manufactured at TU/e; it is expected that cost will decrease with large scale production of these devices.

Figure 17 shows composition of the ceiling access point with WDM over POF fronthaul. POF transceivers are connected to the MXL Evaluation Kit board. Optical signals from and to the optical transceivers are connected to the POF fronthaul infrastructure.

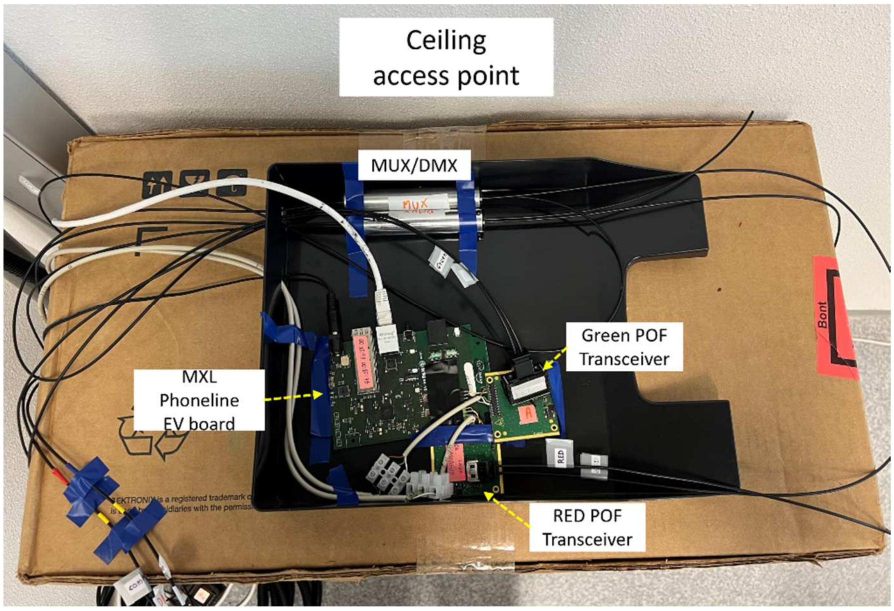

Figure 17 Ceiling access point: MXL Evaluation Kit connected to two POF transceivers and WDM-POF fronthaul components.

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4.2. Measurement Results

The measurements were realized in two steps, and both PHY and TCP throughputs of the bidirectional link were measured. To check if the POF fronthaul can deliver enough throughput to the wireless link, the performance of WDM-over-POF fronthaul is separately measured first. In the second step, the performance of the concatenation between WDM over POF fronthaul and a 2x2 D-MIMO LiFi wireless link is measured considering the user device in different locations. To test MIMO capabilities, the G.hn phoneline boards are configured with the 100 MHz phone line MIMO profile. The WDM fronthaul have been tested for 10 m POF length. For indoor applications, usually lengths between 3 m to 10 m are sufficient.

In Figure 18, the measured throughputs of WDM-over-POF fronthaul are presented. As it can be observed, the measured physical performance is lower than the 1.7 Gbps that can be achieved by the chipset over phonelines. Lower performance is justified by the additional losses inserted in the link by the optical MUX/DMX devices and additional crosstalk in the wavelength domain. Despite this, the WDM over POF fronthaul has shown to be able to deliver gigabit connection with approximately 1.3 Gbps in the downlink direction and approximately 1.2 Gbps in the uplink direction. As both systems are symmetric, both downlink and uplink directions achieved almost the same performance. The small difference is justified by small differences in values of electronic components in the circuits and optical devices.

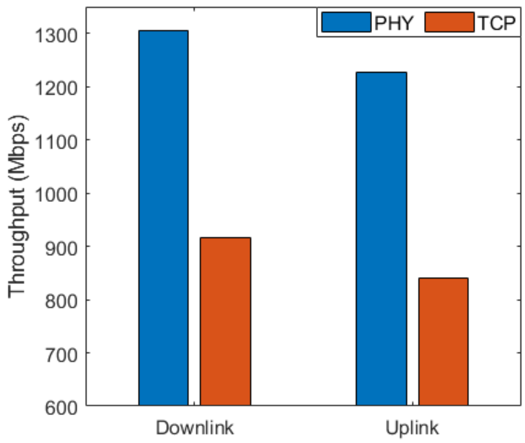

Figure 18 Raw and iPerf measured throughput for the WDM over POF link, considering 10 m of fronthaul length.

In the second step, the downlink/uplink data rates were measured at five different client device locations for the system composed of a WDM-over-POF fronthaul feeding a 2x2 D-MIMO LiFi link shown in Figure 11. Maximum (downlink/uplink) PHY throughputs of 318/213 Mbps are achieved in the middle of the coverage area. Using TCP protocol, the corresponding measured net data rates are 218/144 Mbps. This performace shows that there is enough optical separation between the OFEs of the client device and the client device is able to receive and transmit signals from and to the two luminaries in the ceiling when placed at the middle of the coverage area. The throughput is improved due to multiplexing gain from MIMO spatial multiplexing. At the edges of the coverage area, i.e., when the client device is in front of one of the LiFi OFEs, the measured PHY thoughput drops to 287/177 when the user is in position 1 and to 275/180 when the user is in position 5. The corresponding TCP data rate drops to 192/121 Mbps and 186/121. The performance drop in this case is explained by the

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high crosstalk level experienced by the client device when located in this region. The difference between downlink and uplink perfromances is mainly caused by optical channel differences. The throughput can still be improved by changing the radiation pattern of the optical components and improving the algorithms for crosstalk management in the next generation of chipsets.

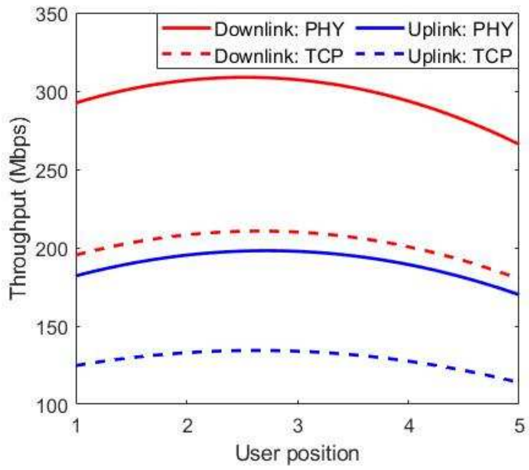

Figure 19 Measured (downlink and uplink) throughput perfor-mance WDM-over-POF fronthaul feeding a 2x2 D-MIMO LiFi link.

In comparison with the previously reported results of the MXL evaluation kit using powerline profile and CAT5 fronthaul, the measured results with the phone line evaluation kit and WDM-over-POF showed better performance. This can be caused by the additional protocol overhead for interference management in the powerline profile and the ability of the phoneline modem to use larger bandwidth than the powerline modem. In general, WDM-over-POF infrastructure would also have advantage in comparison with a CAT5 fronthaul with respect to sensitivity to electromagnetic interference (EMI).

4.3. Cell-to-cell handover setup

Multiple ways can be envisioned to handle the spread of users over a larger coverage area as shown in Figure 20. Specific characteristics of the different multi-user handling schemes are given in Figure 21.

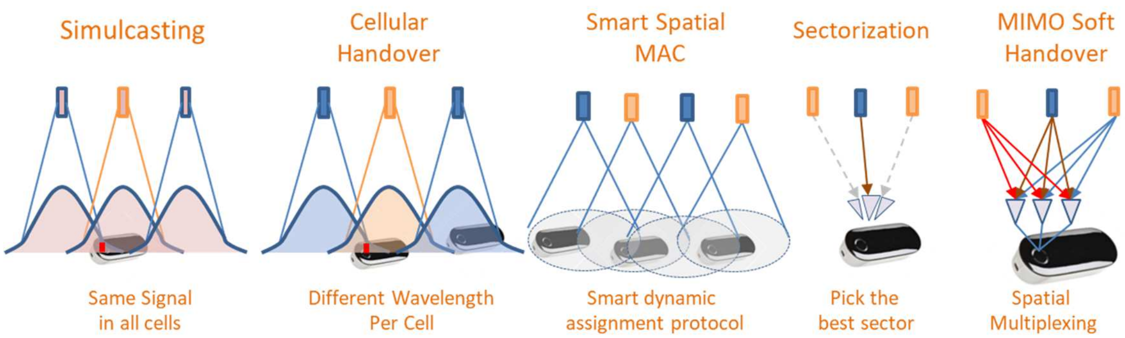

Figure 20: Multi-user handling schemes in Office LiFi system.

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	Simulcasting	*Handover*	*Spatial MAC*	*Sectorization*	*D-MIMO*	*MU-D-MIMO*
Complexity	Low	Medium	High	low	High	Very High
Spatial reuse	No	costly	Spatial reuse	no	No	Spatial reuse
Power efficiency	poor	medium	good	good	good	medium
Layer	PHY	MAC	MAC	PHY	PHY	PHY and MAC
Standard compatibility	Mature	Good	Good	Good	Shown, improvements advised	Requires major enhancements
In office demo	tested	No	No	Some aspects	Yes	No

Figure 21: Comparison of multi-user handling schemes.

5. Demonstrator video

The video of the Office demonstrator can be found at the ELIOT website: https://www.eliot-h2020.eu/

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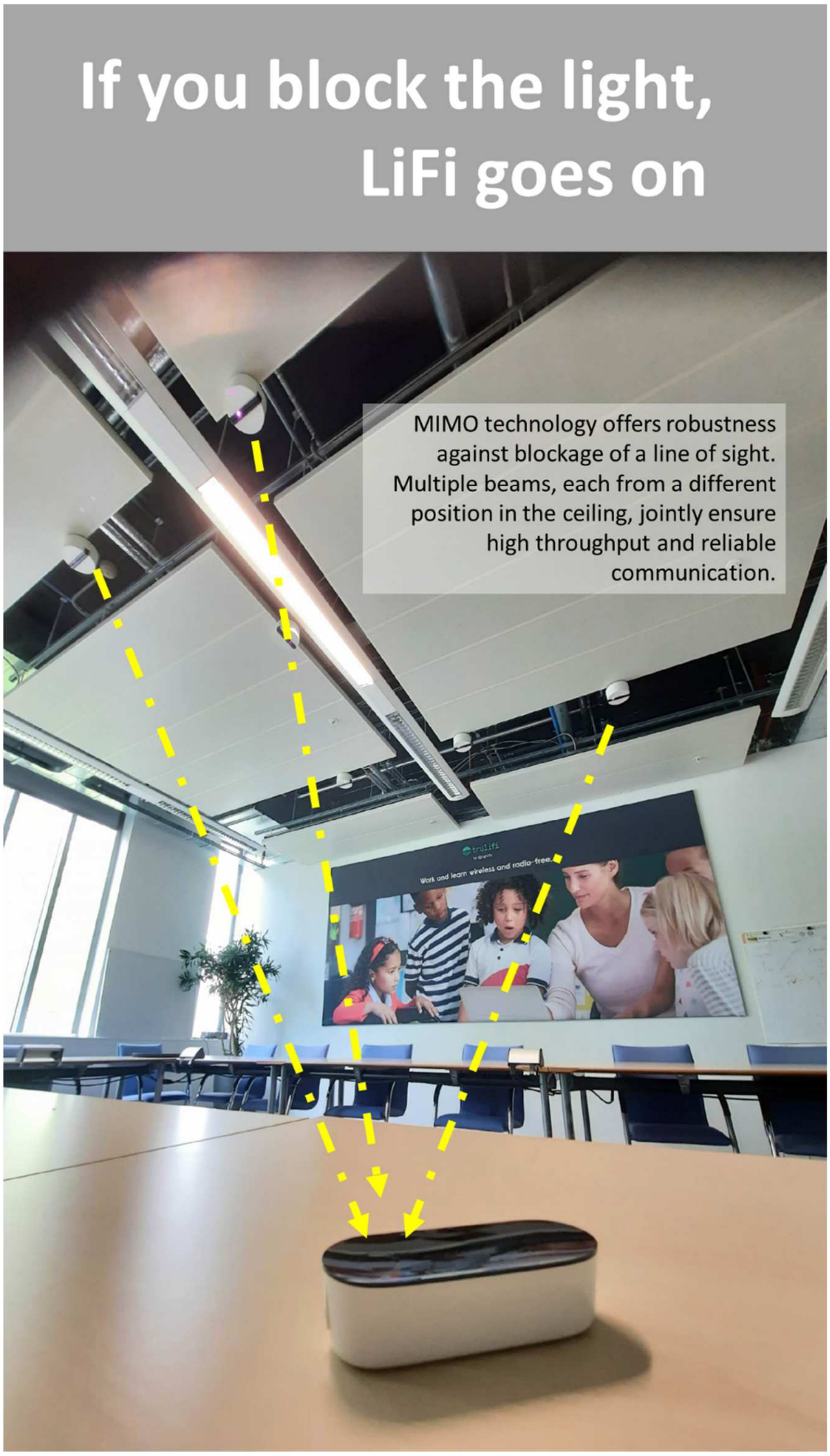
6. One-liner summary



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7. Conclusions

This Office Demonstrator intends to show capabilities of LiFi in serving the data communication needs of a typical office environment. With growing bandwidth requirements of modern applications, such as video conferencing, LiFi can play a significant role especially in densely occupied offices. In such settings, the LiFi network can augment WiFi by reducing network congestion. The demonstrator has been built using various components developed by project partners and proves that LiFi will still function properly under partial blockage of a light beam. To this end, different tests have been conducted to investigate system performance for different usage scenarios. The various observations from this demonstrator and results from earlier ELIOT work packages help to identify limitations of current technical solutions and generate inputs towards 2nd generation ITU G.VLC standards.

Summary of demonstrator

We have tested to what extent the current chipsets allow MIMO to run in powerline and phoneline profiles. It gives us confidence that next generation chipsets, for instance in which the coax profile is extended to MIMO operation, can enhance performance. It also indicates that certain improvements to the standard and to the implementation are highly desirable to improve the response speed to changing channel conditions.

Additionally, we have shown that the fronthaul infrastructure to support D-MIMO can be implemented using either CAT5 copper cable or POF, the latter being less sensitive to EMI.

Relation to ELIOT objectives

O7.1: This effort to set up a demonstrator gave important learnings that could be used to improve standardization such as IEEE, ITU-T and led to insights reported in publications at conferences and in major journals and magazines and to make project achievements accessible through a project website, and present project achievements at numerous public events.

O7.2: This effort to set up a demonstrator gave input to the economic analysis considering realistic market potential of LiFi as it also addressed options to implement the fronthaul in a cost-effective manner. In fact, the economic analysis confirmed that the cost of the fronthaul is an essential factor.

O7.3 This effort to set up a demonstrator helped to sharpen private and public exploitation plans for VLC. The demonstrator allowed partners to update them during the project regarding the project results and to discuss changes, challenges, and issues.

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8. References

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