Using G.vlc in MIMO LiFi, the experience with Phoneline and PLC profiles

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Note for Reviewers and TPC: The authors have been invited to describe these ELIoT findings in an euracip journal. We may can present the full story, but we have to limited the written material at OWCC

1. Introduction

While radio-frequency (RF) communication dominates internet access today, it is not a good solution for environments where connection stability, low latency, and high security are strong requirements. For these scenarios, Light Fidelity (LiFi), a technology which uses electromagnetic waves in the visible or infra-red range of light, has been seen as a great alternative for free-space transmission. The growth of LiFi is also motivated by the need for a complementary solution to the crowded RF spectrum. Since light is confined by boundary walls, the entire spectrum used inside one room can be reused in neighbouring rooms. Consequently, LiFi is able to provide increased user density (bit/s/m2) with high security and a guaranteed level of quality-of-service (QoS), critical features required by, among others, internet of things (IoT) and in industry 4.0 applications.

Despite its advantages, the use of narrow light beams for communication has a weakness. In LiFi, since the non-line-of-sight (NLOS) channel is much weaker than the line-of- sight (LOS) channel, if the LOS link is blocked, a system which uses only one transmitter and one receiver has a high probability to fail. A solution for this problem, that is widely used by the lighting industry, is to provide uniform shadow-free illumination, which consists of the transmission of multiple signals through multiple light sources distributed over the ceiling of a room. The use of multiple transmitters and multiple receivers, widely employed in RF systems, is known as multiple-input multiple-output (MIMO) transmission schemes. MIMO is key in LiFi systems to improve robustness and increase data throughput.

The ITU G.9991, also known as G.vlc, specifies a 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 G.hn (G.9960) standard, which provides a high-speed backbone for both LiFi and WiFi applications [1]. G.vlc defines important features for dealing with the bandlimited and low-pass response of light sources commonly used in LiFi systems such as light-emitting diodes (LED). These features include orthogonal frequency-division multiplexing (OFDM), adaptative bit-loading, MIMO, M-ary quadrature amplitude modulation (QAM) and others. To accelerate LiFi adoption, a range of solutions entered the market using available G.hn chipsets. These chipsets are designed for home networking with data rates up to 1.7 Gbps operating over powerline, coax, twisted pair and plastic optical fibre. Nowadays, these chipsets are employed in LiFi systems, but the question regarding whether they are mature enough to solve LiFi challenges is still open.

In this context, the project "Enhance Lighting for the Internet of Things" (ELIoT) has been working on innovations to enhance the ITU G.9991 LiFi standard, e.g. [2]. In ELIoT, the use of LiFi systems in different link conditions is tested experimentally. The obtained results have allowed the project to gather valuable information that now needs to be reinjected into the chipset community. To build the experimental setups, project partners have focused on G.9991 compliant chipsets, since G.9991 is one of the first standards that have been approved in the light-based communication field and that provides the advantage to have several chipsets already available in the market.

This work provides an overview of the experimental results of using G.vlc in MIMO LiFi from both Eindhoven University of Technology (TU/e) and Signify Research labs. The technical findings highlight that, for a better LiFi experience, features such as faster channel estimation, profile selection, MIMO channel adaptation and MIMO change of mode, still have to be included in the next generation of components and standard recommendations. The discussion also opens the door for new research topics that have been identified as interesting paths for future projects beyond ELIOT timeframe.

2. Measurement results

The MaxLinear G.hn wave-2 products provides high-speed networking solutions for different wired mediums such as, powerlines, phone lines and coaxial cables [3]. It can provide physical layer data rates up to 1.7 Gbps over phone line and coaxial cable, and up to 1 Gbps over powerline. MaxLinear G.hn wave-2 platform supports features such as single-input single-output (SISO) with 200 MHz bandwidth on phone lines or on coaxial cables and MIMO with 100 MHz bandwidth on phone line or on powerline profiles [1]. An evaluation kit is available for each wired medium. In this work, the performance of G.hn in a 2x2 MIMO LiFi system for various link conditions is investigated using both a MaxLinear G.hn wave-2 phoneline evaluation kit and a MaxLinear G.hn wave-2 powerline evaluation kit [1].

To compose a 2X2 MIMO LiFi link, four Trulifi transceivers from Signify are used. They are connected to the analog front ends (AFE)s on the board of the MaxLinear G.hn Wave-2 Phoneline or of the Powerline Evaluation KITs using ethernet CAT5 cables with 2.8m length each. The CAT5 cables are responsible for carrying both data traffic, and 24V DC power to feed the optical frontends (OFEs). For the powerline profile an extra interface adapter is introduced between the AFE and the CAT5 cable [4]. A block diagram of the experimental setup is shown in Fig. 1. Each one of the Trulifi transceivers is an OFE equipped with one IR LED and one photodiode. For the interested reader, a brief description of the device can be found in [5]. To test MIMO capabilities, each MaxLinear board is configured with the 100 MHz MIMO profile.

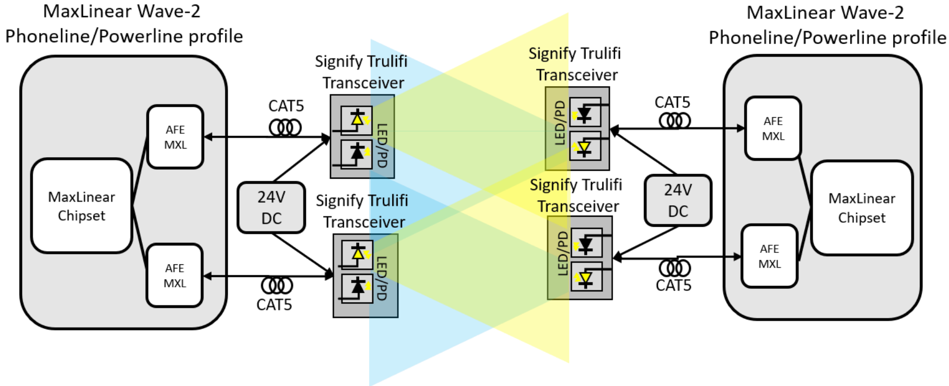


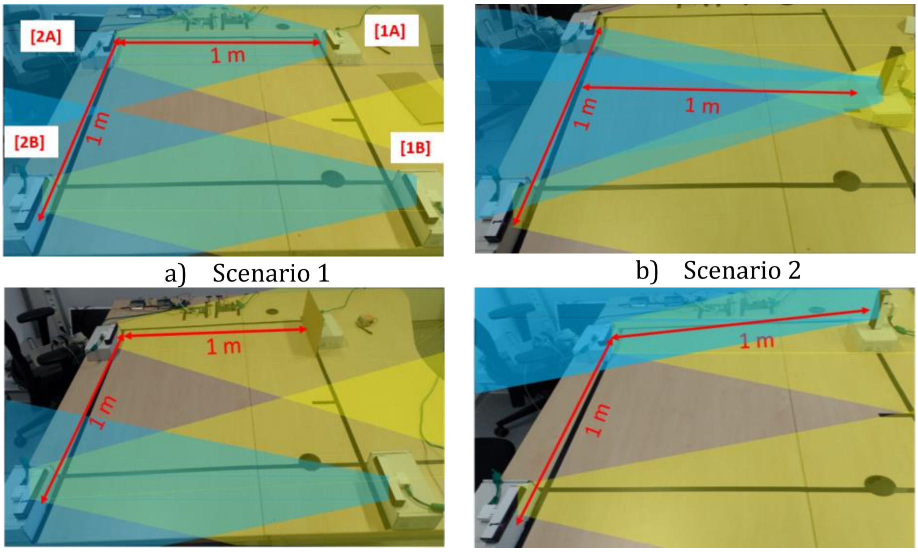
Fig. 1: G.vlc in MIMO LiFi with phoneline or powerline profiles.

At TU/e, the performance of G.vlc in MIMO LiFi is evaluated by using a MaxLinear Evaluation Kit for phoneline profile. MIMO performance was measured in four different scenarios. In scenario 1, the 2x2 MIMO LiFi system is evaluated over a less-correlated channel. A picture of the test setup is shown in Fig. 2(a) where both user (1A, 1B) and ceiling (2A, 2B) devices are placed on a table. This basic arrangement is used to verify LiFi operation under various link conditions. In this scenario, the optical front ends of both celling and user units are 1 m away from each other. Considering the viewing angle of the LEDs of approximately 60 degrees, signals that comes out from interference channels do not reach the desired channels. Consequently, in this case, the MIMO channel matrix is well-conditioned. Interference from adjacent transmitters is negligible and the achievable data rate of the system is mostly limited by noise. This scheme is intended for estimating the achievable data rate by G.vlc in a MIMO LiFi system using spatial multiplexing (SM).

In scenarios 2 and 3, the 2x2 MIMO performance is investigated in a high correlated channel, i.e., where the level of crosstalk between the channels is high and the expected throughput for SM is low. In scenario 2, the OFEs on the ceiling are again 1 m apart, but both optical front ends on the user's side are placed very close to each other. This would represent a real mobile use case, when LEDs and PDs are mounted with a small separation such as in devices like smartphones or laptops. In this example, LEDs and PDs at the user side are separated only by a small tilt placed between OFEs. The user is then positioned in the middle of the distance between the ceiling OFEs, but 1m away from them. It is exactly situated in the overlapping area between the optical beams of the downlink channel. In this case, the crosstalk level would be high, but the small angle between OFEs leads to a channel correlation reduction.

In scenario 3, the user is positioned in front of one of the OFEs of the ceiling node. The distance between OFEs of the ceiling node is kept at 1 m, and the OFEs of the user node are 1 m away from the ceiling. As in the second scenario, the OFEs of the user node are kept close to each other, only separated by a small angle. As the viewing angle of the LEDs is approximately 60 degrees, the PDs of the user are only able to receive signals from the OFE that is in front of it. Consequently, the 2x2 MIMO downlink channel can be approximately represented by a 2x1 vector of coefficients which contains the channel gains between the LED from OFE that is in front of the user and the PDs of the user. In the uplink channel, only one OFE of the ceiling node can receive signals from both LEDs of the user node. In this case, the 2x2 MIMO channel matrix reduces to a 1x2 vector of coefficients which contains the channel gains between the LEDs of the OFEs of the user node and the PDs of the OFE of the ceiling node. In a SM scheme, the transmission of two different signals over an overlapping coverage area would lead to a reduced throughput since both signals interfere with each other, however, in a spatial diversity scheme (SD) the overlapping areas would contribute to higher signal-to-noise ratio (SNR) thanks to the constructive interference. Therefore, in both second and third scenarios, the centralized signal processing should be able to choose for spatial diversity (SD) and then switch from SM to SD in order to achieve a good SNR and, consequently, a reasonable performance.

In scenario 4, the optical wireless link is exposed to link blockage. In this case, the communication link of one of the Trulifi transceivers is interrupted by an obstacle. In this case, communication would not be lost as MIMO would be able to stablish connection via the unblocked link. An illustration of the four link conditions is shown in Fig. 2.



a) Scenario 1 b) Scenario 2

d) Scenario 4 c) Scenario 3

Fig. 2: Illustration of the four different link conditions investigated with G.hn for phoneline profile.

The link performance was measured with a network evaluation tool IPerf [6]. IPerf is a tool widely used by network designers to measure throughput and the quality of a network link. The measured throughput of both uplink and downlink for each one of the four analysed scenarios with the G.hn for phoneline profile is shown in Fig. 3.

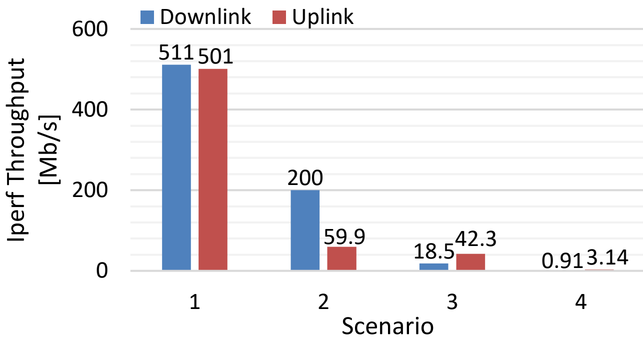
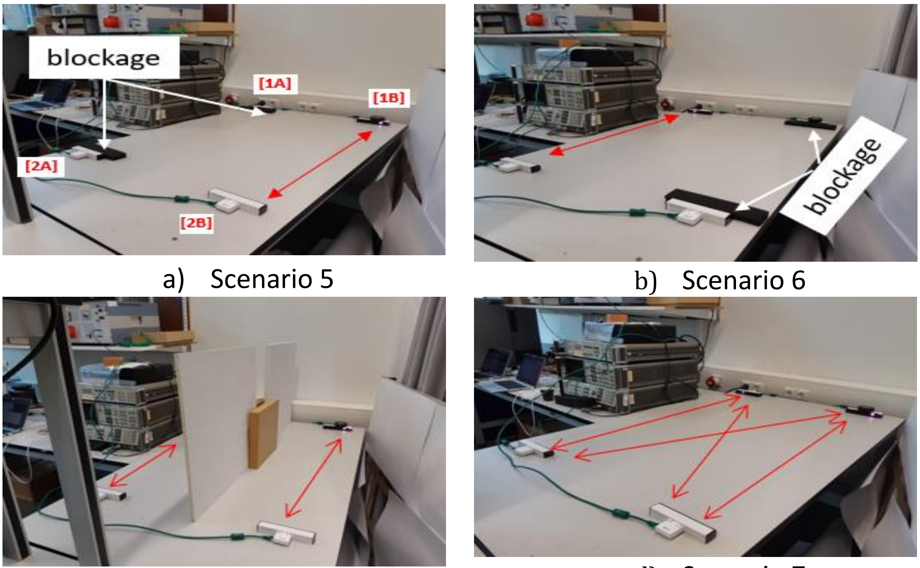


Fig. 3: Throughput measured using IPerf software for the four link conditions using G.hn for phoneline profile: Scenario 1: Low correlated channel. Scenario 2: User OFEs are closely placed and are positioned in the middle of the coverage area. Scenario 3: User OFEs are closely placed and are positioned in front of one of the OFEs of the ceiling node. Scenario 4: One of the OFEs of the user node is blocked.

Despite the large spacing between the optical frontends at the user side, which does not really represent a user device in a mobile use case, scenario 1 is useful as a reference of the upper limit of the achievable throughput due to its low crosstalk level. The measured throughput of 511 Mb/s at the downlink channel is similar to the throughput of 501 Mb/s measured at the uplink channel due to the symmetry in the distribution of the OFEs. Comparing the throughput of scenarios 2 and 3 with the measured performance of the scenario 1, it is possible to observe a huge performance drop. This decline in data rate can be explained by the increase in crosstalk channel gains which increases interference from adjacent transmitters leading to lower throughput [7]. In these scenarios, the correlation between desired and interference channels is high and the data recovery processing is not able to distinguish desired streams from interference streams. A probable solution would be to switch from SM to SD to improve the SNR. However, MIMO mode switching is not implemented in the current chipset yet. In scenario 4 one of the optical links is blocked and the observed throughput is very low. The measurement was repeated many times but, unfortunately, adaptation of the link was not possible to start communication through the unblocked link.

At Signify, the performance of G.vlc in MIMO LiFi is investigated by using a MaxLinear evaluation kit for powerline profile. For this, eight different link conditions were tested. At 120cm distance and 60° opening angle of each OFE, the beams from two OFEs placed 60 cm apart will overlap at the receiving end allowing MIMO communication. Additional arrangements, where the OFEs on the user side are closely placed, are also derived to emulate the final arrangement of a small dongle. This experiment is conducted with the user OFEs spaced by 60cm to obtain reference link performance data under idealized test conditions. In practice the user side OFEs will be closely spaced due to space limitations. Various arrangements for this experiment are shown in Fig. 4. The SISO links in Fig. 4(a) and in Fig. 4(b) are obtained by placing a blocking material in front of the OFEs that face each other. The MIMO arrangement in Fig. 4(d) is created by adding separation material to block beams from adjacent OFEs.



a) Scenario 5 b) Scenario 6

c) Scenario 8 d) Scenario 7

Fig. 4: Test setup arrangements to evaluate link performance of G.hn for powerline profile in MIMO LiFi when the user side OFEs are spaced by 60 cm.

The link performance data for the test arrangements in Fig. 4 are given in Fig. 5 Due to symmetry of the layout and the OFEs used, only the downlink, i.e., ceiling-to-user data transfer is considered. Both MIMO arrangements provide equivalent throughput, close to double the SISO links.

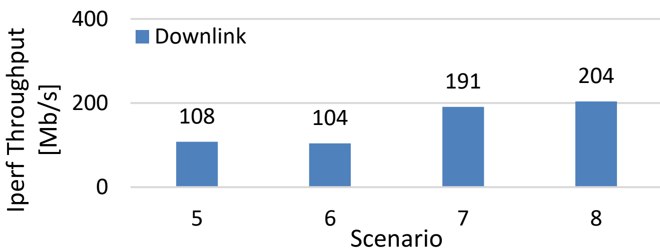
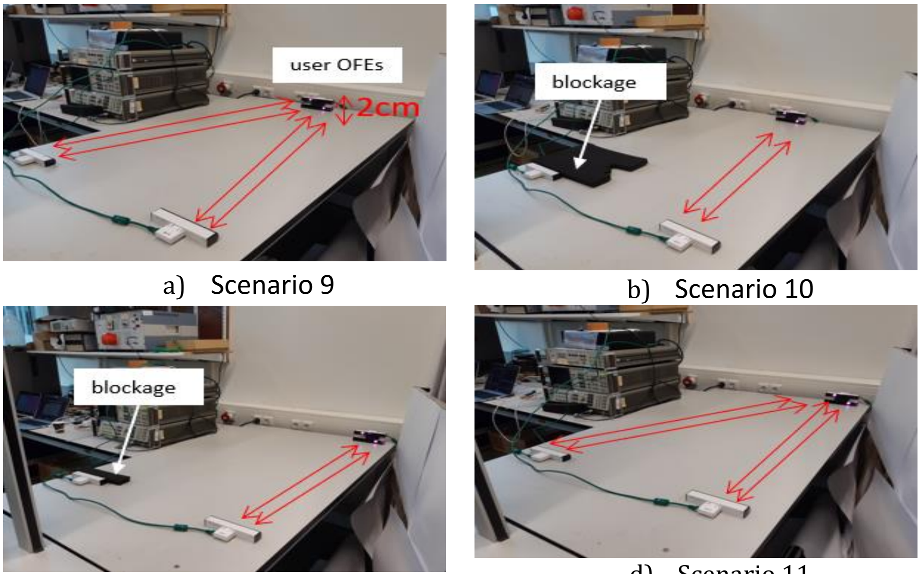


Fig. 5: Throughput measured using IPerf software for link conditions 5-8 using G.hn for powerline profile.

A more practical test arrangement is to place the user side OFEs close to each other (approximately 2cm gap) as depicted in Fig. 6. Cases shown in Fig. 6(a) and in Fig. 6(b) are used to test 2x2 MIMO operation when the user device is placed at the center of the coverage region and at the edge, respectively. To test the loss of LOS to one of the ceiling OFEs, the beams are blocked as shown in Fig. 6(c) and in Fig. 6(d).



a) Scenario 9 b) Scenario 10

c) Scenario 12 d) Scenario 11

Fig. 6: Test arrangement where the user OFEs are placed together to model practical use cases.

The link performance data of these test arrangements is given in

Fig. **7**. For both up and down link directions, the MIMO options show 12% – 30% more throughput than the MISO arrangements.

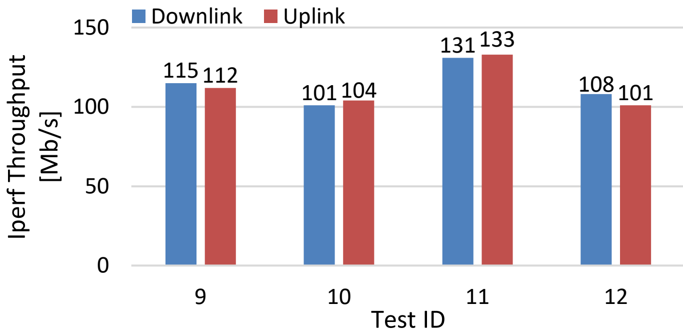


Fig. 7: Link performance when user OFEs are closely place.

Compared to the earlier tests where the user-side OFEs were spaced, the current arrangements show a performance drop. One explanation for this is the relative alignment of the ceiling and user OFEs: in the earlier test, both user-side OFEs directly face corresponding ceiling-side OFEs which maximizes the received optical power. On the other hand, when the user-side OFEs are placed together, the beam from at least one of the ceiling OFEs is received at angle leading to reduced link performance.

3. Link performance under dynamic conditions

The performance data so far related to stable channel conditions where the ceiling and user-side PLC modems start from power-on reset. In practice, the user is mobile and the optical channel characteristics can vary, depending on the relative position between the transmitter and receiver and occasional blockage. To simulate these conditions, a few experiments were conducted by moving the user device in the field of view and blocking some of the OFEs.

The first experiment starts with power-on reset of the user location MIMO close-right (MIMO-CR) aligned as shown in Fig. 6(c). The throughput from the ceiling to the user was monitored when one of the user-side OFE is blocked and un-blocked at different time instants. The result in Fig. 8 shows that the link performance is not repeatable for the same channel change: while the first blockage around 32 s resulted in throughput reduction from 132 Mb/s to 104 Mb/s, the throughput collapsed to 1 Mb/s after the second blockage and did not recover for 500 seconds. The transition from blockage to no-blockage at 106 s took 16 seconds to settle to the new condition. This can be repaired and accelerated to occur within reasonable time by a software upgrade. At the time of writing that was not yet implemented.

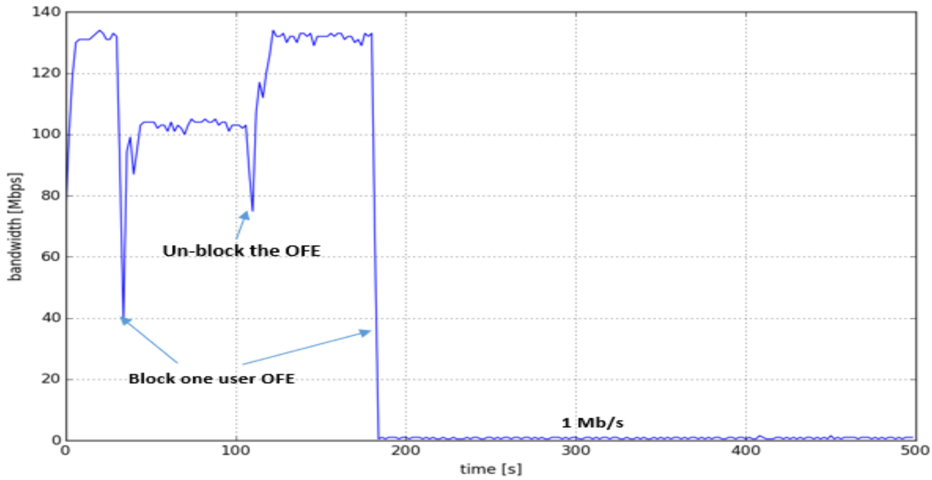


Fig. 8: Link performance when changing channel characteristics by blocking one of the user-side OFEs, before software upgrade to improvea adaptation.

The second experiment was conducted starting at the MIMO close-center (MIMO-CC) aligned system arrangement of Fig. 6 (a) achieving 138 Mb/s and moving the user-side OFEs to the MIMO-CR arrangement of Fig. 6 (c) at 104 s for which the throughput reduced to 133 Mb/s as shown in Fig. 9. Thereafter, the farthest ceiling-side OFE is blocked at 205 s further reducing the throughput to 102 Mb/s. When the blockage was removed at around 287 s, the throughput got back to 130 Mb/s. AT 407 s, the nearest ceiling-side OFE was blocked that resulted in collapse of communication for the following 60 seconds after which the throughput started to toggle between 20 Mb/s and 50 Mb/s. When the blockage was removed at 611 s, the 130 Mb/s throughput was regained.

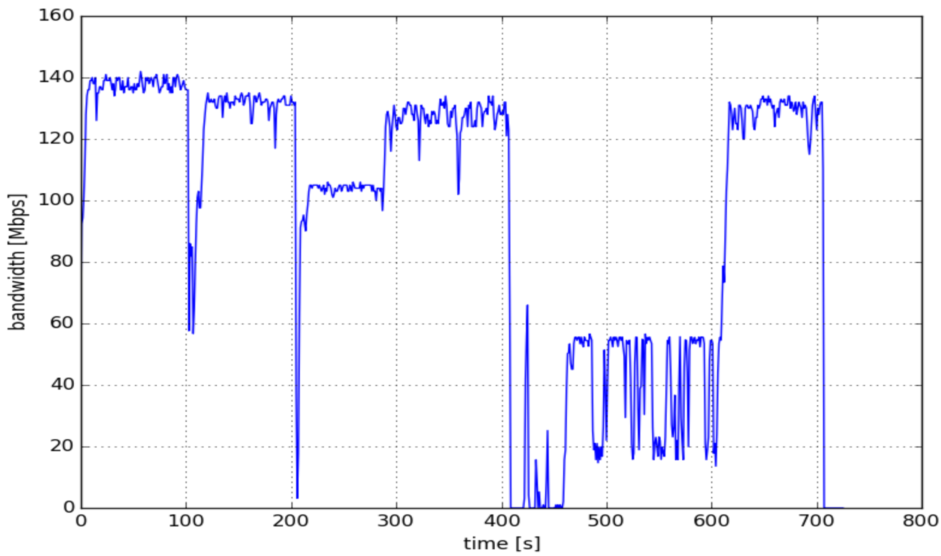


Fig. 9: Link performance when moving user-side OFEs, blocking and un-blocking one of the ceiling-side OFEs.

4. Conclusion

Although the table-top experiments conducted in this work are not in exactly identical circumstances as a real office configuration, they still help unravel the capabilities of using currently available G.hn chipsets for phoneline or PLC profiles in LiFi systems. The main differences between the final application and the table-top experiments include difference in distance between ceiling and user device, imperfections such as reflections from table surface and different user device integration of OFEs. Despite its improved interference mitigation capability, compared to the phoneline MIMO modem, the PLC modem still lacks support for channel characteristics adaptation to handle user mobility. Through our experimental results, we see that there may be situations where G.vlc-based LiFi modems are not fast enough to recover from a channel loss when the mobile user blocks one of the physical channels. The basic principles of D-MIMO, both for diversity and spatial multiplexing are suitable starting points for improvements to communication reliability and throughput enhancements, respectively. However, a number of optimizations for the specific case of LiFi are recommended. Moreover, improvements to the speed of adaptivity, more frequent channel measurements and creating the ability to rapidly switch modes are essential for LiFi and must be included in next generation chipsets and G.vlc standard recommendations.

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