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A European View on the Next Generation Optical Wireless Communication Standard

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***Abstract*—Optical wireless technology uses light for mobile communications. The idea is to simultaneously combine the illumination provided by modern high-power light-emitting diodes (LEDs) with high-speed wireless communications. There have been numerous practical demonstrations of this concept, and the technology is now well matured to be deployed in practice. Independent market analysts forecast a high-volume market for mobile communication devices connected to the ubiquitous lighting infrastructure. This paper aims to make optical and wireless industries aware of the requirement for standardization in this area. The authors present the view of the European COST 1101 research network OPTICWISE towards a next-generation optical wireless standard aiming at data rates from 1 Mbit/s to 10 Gbit/s. Besides key technical insights, relevant use cases and main features are described that were recently adopted by the IEEE 802.15.7r1 working group. Moreover, a channel model is introduced to enable assessment of technical proposals.**

Fig. 1. Vision of a new wireless network using the lighting infrastructure.

I. Introduction

LIGHT has always been used for wireless communications. Ancient examples are fire signals on mountains, the heliograph known since 400 BC, and finally the photo-phone, which was invented by Alexander Graham Bell in 1880. Due to the success of radio in the 20^{th} century and the outstanding achievements of mobile communication introduced around 1990, which offers almost complete coverage for mobile telephony, optical wireless must be considered as niche or complementary technology.

New bandwidth hungry applications being developed are creating a significant further demand for mobile data delivery. In 2020, an additional three orders of magnitude more mobile data traffic is expected in comparison to 2010, while the spectrum for mobile services is to be approximately doubled [1]. This is also referred to as the mobile spectrum crunch and is also addressed by recent research towards a fifth generation (5G) of mobile radio [2–4], where most approaches reuse the spectrum more frequently.

Along with millimeter bands, it is worthwhile to look at the optical spectrum, which is unregulated by a licensing body, and offers practically unlimited bandwidth (400 THz). The idea of an optical wireless network is described in [5]. The potential of diffuse light, enabling mobility even if the line-of-sight (LOS) is not available, has been highlighted in [6–8]. Note that communication is only possible wherever the light can be detected, even if it stems from diffusely reflected photons. Moreover, light can be easily directed using a spot-shaped light source and lens.

Indoors, it is difficult to tap or to jam optical wireless signals from outside a building, thus enabling an enhanced privacy.

Three major achievements were recently made [**?**].

First, the introduction of powerful GaN light-emitting diodes (LEDs) [9] and white light-emitting phosphors [10] enabled visible light sources at low cost. Illumination LEDs can be modulated at much higher speed than any previous lighting source (commercial LEDs have modulation bandwidth of 10-20 MHz). In the future, LED lighting is expected to be available everywhere. Because fast modulation is possible besides the basic lighting function, a new mobile communication technology is envisioned by considering individual luminaries as an access point, fed via the powering infrastructure.

Second, reflected light being also detected at the receiver can cause a severe multi-path effects. Moreover, if the user is mobile, the optical wireless channel can rapidly vary. The benefit of orthogonal frequency-division multiplexing (OFDM) in combination with adaptive transmission has been highlighted by several reports [11–13]. OFDM allows simple equalization in the frequency domain. If channel state information (CSI) is provided as feedback, in addition, closed-loop dynamic link adaptation becomes possible. The so-called adaptive OFDM enables a robust wireless link despite critical channel properties and a very high bit rate despite the limited bandwidth. Up to 1 Gbit/s (single channel) and 5.5 Gbit/s (multi-wavelength) were demonstrated in directed line-of-sight configurations. Hundreds of Mbit/s (single channel) are feasible with wider hot spot areas (20 m^2) [14–16].

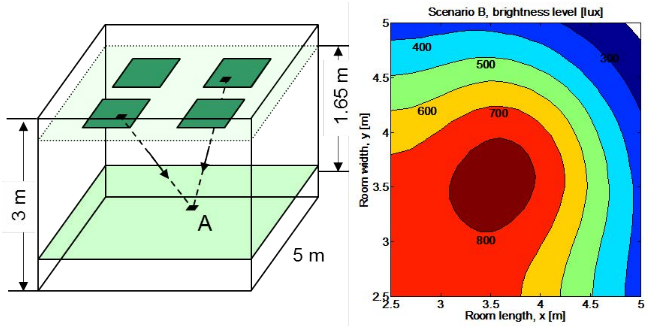

Fig. 2. Left: Indoor scenario with four LED transmitters at the ceiling. Right: Achievable illuminance in lux in one quarter of the illuminated area.

Finally, handover and multiple access are main features of a mobile technology. Horizontal handover enables the user to be served by multiple cells and stay connected in the coverage area of the lighting infrastructure. Overlapping cells reuse the optical spectrum, hence, mutual interference requires some kind of coordination [17–20]. Recent research assuming practical techniques show that a LiFi network could achieve 40 to 1.800 times higher data rate, compared to femtocell radio networks in the same area because optical signals can be better confined [21]. Moreover, vertical handover, together with channel bonding, enable an efficient use of optical wireless in parallel to other mobile technologies in the same area [22].

To include these features in a single word, the term LiFi was coined for a new mobile access technology based on visible light. The combination with the lighting infrastructure opens a potential path into a mass market.

A complete new ecosystem is envisioned for optical wireless, including infrastructure vendors, network operators and device manufacturers. Obviously, there is a need for a standard that enables interoperability and lowers the cost.

In this paper, the key insights for the system design are summarized in Section II. Promising use cases are outlined in Section III. Features of a next generation standard and channel modeling are described in Sections IV and V, while the way forward is discussed in Section VI.

II. Key Insights for the System Design

Efficient high-power blue-emitting LED sources became readily available at low costs due to advances in GaN bandgap engineering [9]. GaN LEDs could be modulated at high frequencies, however the relatively large semiconductor photoactive area and intrinsic carrier lifetimes impose well-defined limitations on the modulation speeds. Specific high-frequency driver circuits in front of the LED can overcome the capacitive effect caused by the large photo-active areas, enabling bandwidths of up to 175 MHz with off-the-shelf LEDs [23, 24].

White light is normally produced by using a color-converting phosphor coating due to low implementation costs [10]. As high-power LEDs are also available for red and green, so-called RGB LEDs yield white light as well, thus enabling a second method of white light generation by combining each source, and subsequently enabling the independent modulation of each color, which is denoted as wavelength-division multiplexing (WDM).

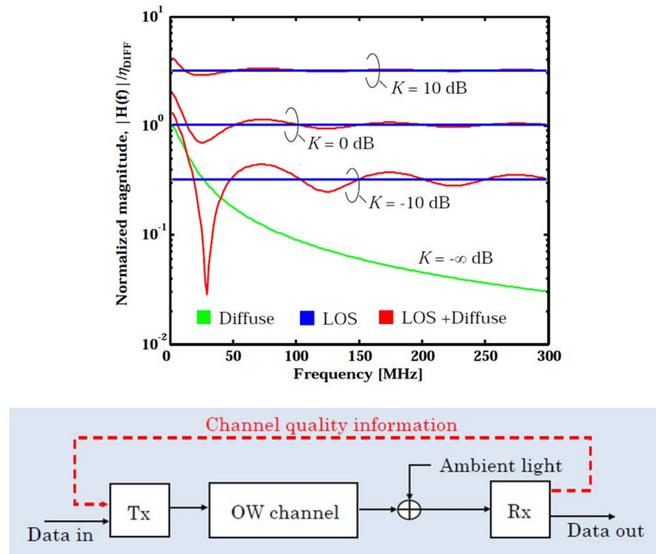

Fig. 3. Top: Frequency response for different power ratios of LOS and reflected signals, denoted by K. Bottom: Concept of closed-loop adaptive transmission.

The light can be absorbed either with silicon P-I-N photodiodes (PDs) and avalanche photodiodes (APDs), where intrinsic amplification offers higher sensitivity. However, APDs are costly and need a high reverse bias voltage. At typical diameters of a few millimeters, a PD combined with a well-designed transimpedance amplifier (TIA) can reach a similar performance as an APD at a much lower cost [25]. Prototypes offer 100 MHz bandwidth with around 1 cm effective PD diameter [23]. Lasers might offer more bandwidth at the transmitter, however in order to use the advantage at the receiver, a smaller PD or an array with individual TIA per pixel are needed. Together with lens, each pixel receives signal from a specific direction what is useful for directive applications.

A key insight is that optical wireless systems have to be designed for high signal-to-noise ratio (SNR). In Fig. 2 left, a typical scenario using bright white LEDs is shown. For details, refer to [26]. In Fig. 2 right, showing one quarter of the illuminated surface, an illuminance between 400 and 800 lux across the entire coverage area is reached. The received light translates into theoretical SNR values of more than 60 dB at the receiver. Due to the high illuminance achievable, high spectral efficiency is the key to achieving high data rates within the limited modulation bandwidth of the LED.

The channel between transmitter and receiver is often a superposition of the LOS with one or more multi-paths signals due to specular or diffuse reflections. Note that the power ratio between LOS and non-LOS components, also denoted as the K-factor, is crucial, see Fig. 3, top. If the LOS is dominant (large K), the channel supports a huge bandwidth. But if the LOS is blocked (K is zero), the bandwidth is suddenly reduced [27, 28], see Fig. 3, while the link is still capable working even under such NLOS conditions. The channel can be either flat of frequency-selective, depending on the scenario. And if the user is mobile, over time, the channel can change so that it can offer any gain at any frequency at any time.

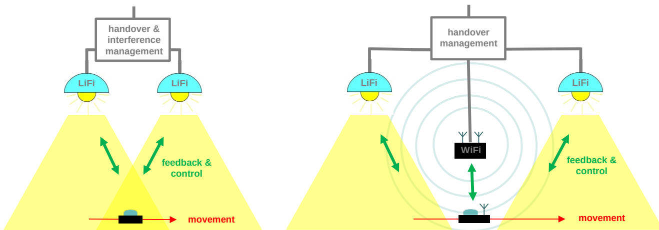

Fig. 4. Left: Horizontal handover between overlapping cells. Right: Vertical handover in case of non-overlapping cells.

Accordingly, optical wireless systems need efficient tools for channel estimation and dynamic equalization at the physical layer as well as adaptive transmission at the medium access layer as key enablers for mobility at the link level, see Fig. 3, bottom. Adaptive transmission is also a key to overcome impairment effects, such as additional noise due to ambient light. While simplified channel models are often used in academics, standards prefer models reflecting more concrete deployment scenarios. This demand can best be served by ray tracing nowadays, see Section V.

In order to provide illumination and mobile communication in a wider area, multiple luminaries need to be used. The coverage of the light can be overlapping or non-overlapping. In the overlapping case, the light is reused in each cell and there is mutual interference among the cells. Interference can be managed with sophisticated techniques, depending also to the users served in parallel in adjacent cells, and performance in the multi-cell scenario depends on smart algorithms. With appropriate interference management, horizontal handover (Fig. 4, left) can be implemented to offer mobility across overlapping cells [20]. For non-overlapping cells, vertical handover is useful between LiFi and another mobile technology to cover the gaps (Fig. 4, right. Mobility is supported by switching the link to the other technology, such as WiFi (Fig. 4, right). Where both technologies are available, channel bonding is very efficient [22].

Note that link adaptation, handover and interference management are functions of higher layers which are usually outside the scope of standardization activities. However, efficient support of such functionality can be provided in a standardized manner from the physical and medium access layers, to deliver feedback reports to a central management entity and to process control messages inside the physical and medium access layers.

III. Use Cases

Future use cases can be classified into four groups (Fig. 5):

1) Indoor Office/Home Applications: These use cases include conference rooms, general offices, shopping centers, airports, railways, hospitals, museums, aircraft cabins, libraries, etc.. It is common to these use cases that *i)* communication range is shorter than WiFi and comparable to Bluetooth, *ii)* user are served by multiple access points, *iii)* a fixed infrastructure featuring a central controller is available, *iv)* users are slowly mobile.

2) Data Center, Industrial and Secure Wireless Scenarios: The use cases address industry scenarios such as manufacturing cells, factories and hangars, with multiple access points serving e.g. multiple mobile robots. These scenarios aim at increasingly personalized production for which mobile communication is essential. Principle technologies may be the same as the above, however, the industrial use case asks for *i)* more robust links, *ii)* lower latency for closed-loop industrial control, *iii)* higher mobility, *iv)* precise positioning support, *v)* enhanced privacy.

3) Vehicular Communications: Vehicle-to-Infrastructure (V2I), Vehicle-to-Vehicle (V2V): Vehicular optical wireless links use the front- and backlights of cars. Note that radio-based solutions may not ensure time-critical message dissemination in dense traffic scenarios because of increased RF interference [29, 30]. The V2V use case is similar to the two previous scenario groups, however, it needs *i)* even higher mobility, because coverage is often incomplete, and very short communication bursts which need ultra high-speed transmission, *i)* robustness against longer multi-paths *iii)* fast link setup and network coordination, *iv)* ad-hoc functionality for V2V having no fixed infrastructure so that coordination is taken over by the device initializing the link setup.

4) Wireless Backhaul e.g. for Small Cells, Surveillance, LAN Bridging: Functionally, the backhaul is point-to-point. However, it is useful to include it because it needs *i)* adaptive transmission not yet available in free-space optical communications to overcome variable weather conditions, *ii)* vertical handover/channel bonding to include parallel radio links as a fall-back solution, *iii)* high speed up to 10 Gbit/s, *iv)* low latency for 5G and the Internet-of-things (IoT).

Note that some of these use cases are also addressed by mm-wave technology, which is another key driver for the forthcoming 5G system, like optical wireless. While a comprehensive comparison is outside the scope of this paper, a concise overview can be provided. While both technologies may use the existing powering infrastructure, radio transceivers and antennas are not needed and the access point can be identical with the new, energy-efficient luminaries based on LED. Light does not penetrate through walls. In secure wireless applications, thus, optics has an advantage because, indoors, it cannot be jammed or tapped from outside a building. In mobile scenarios at mm-wave frequencies, Doppler effects become very important, unlike in the optical domain. The large-area PD averages the received power over many optical wavelengths, so that only the slower variation of the mean optical power is relevant for the time variance of the channel [25]. Longer feedback- and control-loop delays can therefore be tolerated, which enables simpler implementation with less overhead. For the same physical reason, optical wireless may be more suitable in some vehicular use cases. Finally, in the backhaul use case, optical wireless links may be useful over shorter distances where the fog is less relevant (few 100 m, see [31, 32]), while long-distance and NLOS links can be better served by mm-waves where coherent reception is more sensitive than the direct detection used for optical wireless. Moreover, mm-wave reflections are more specular and can be used when the LOS is not available [33].

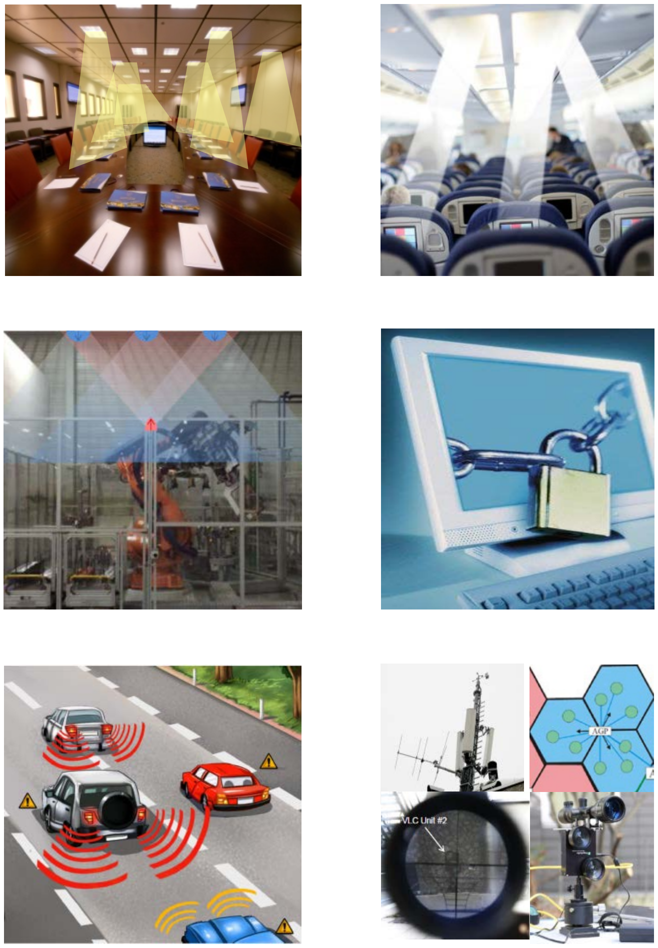

Fig. 5. Exemplary optical wireless use cases: Top left: Conference room. Top right: Aircraft cabin, Center left: Industrial scenario, Center right: Secure wireless scenario, Bottom left: Vehicle-to-vehicle communication, Bottom right: Wireless Backhaul.

IV. Main Features

These envisaged use cases have been recently adopted by the working group preparing the IEEE 802.15.7r1 standard. They formed the basis for identifying prospective mandatory and optional features. In this Section, the main features are summarized [34].

Ceiling and street lights will be used in cases $1-3$ in Section III, indirect light for 1 and 2, car lights in use case 2 and directed light in 2 and 4. Modulated light that can be seen by the human eye shall be safe in regards to the frequency and intensity of light (e.g. IEC 60825-1:2014) and it will not stimulate sickness such as photosensitive epilepsy. Dimming control is envisaged for use cases $1-3$. Co-existence with ambient lights is foreseen. This may enable a receiver to communicate with a supported transmitter even in the presence of other modulated lights.

Both, continuous data streaming for all applications as well as short packet transmissions will be supported where low latency is required. Efficient use of the available optical bandwidth of a given luminaire is mandatory for all use cases. Communication shall support data rates from 1 Mbit/s to 10 Gbit/s depending on the use case. At 1 Mbit/s, e.g. wireless access to a cabin management system in an aircraft shall be possible in the whole cabin. At 10 Gbit/s, obviously, the backhaul use case is currently addressed. Asymmetric communication between transmitters and receivers shall allow higher data rates in one direction. Coexistence shall be investigated with the existing IEEE802.15.7-2011 operating modes.

Physical and medium access control layers will support adaptive transmission as well as multiple users communicating over different data streams via the same light source (multiple access). Multiple coordinated or uncoordinated transmitters may be supported, referred to as multiple-input multiple-output (MIMO). This may also include cooperative signal processing among multiple transmitters with negligible impact on latency. Efficient and reliable feedback and control channels may be used for adaptive transmission, multiple user support, MIMO support, cooperative signal processing or other features. Mechanisms for horizontal handover between light sources will be supported, allowing the users to maintain a continuous network connection for use cases $1-3$. Additional mechanisms to deliver interference coordination by higher layers and precise positioning may be supported.

Internal metrics may be provided from the physical layer to the network via an open interface to support cooperative signal processing, vertical handover and channel bonding with other wireless transmission techniques. For this purpose, information can be provided about instantaneous signal-to-interference-and-noise ratio (SINR), detailed CSI and the recent history of the channel such as temporal characteristics, signal blocking and frequency of signal losses. For low latency in use cases 2 and 3, short intervals between feedback reports and control messages are needed.

V. The COST 1101 Channel Model

Despite the growing literature on visible light communications (VLC), the number of works on channel modeling is limited. In the past, work on impulse response (IR) channel modeling was mainly based on two approaches, namely recursive method and Monte Carlo ray tracing, see [28, 35, 36] and the references therein. Building on these approaches, some channel models were proposed [37–39], however not taking into account the inherent characteristics of the visible light band that differ from infrared counterpart. For example, reflectance values do not remain constant for all wavelengths. In an effort to address this, the use of averaged values of reflectance coefficients is proposed [40]. Wavelength dependency is more accurately taken into account in [41] where a recursive method is used to determine the channel impulse response (CIR) of an empty room. In addition to wavelength dependency, a realistic channel model should further take into account the effect of light sources, objects within the environment as well as different types of reflections such as specular and mixed diffuse and specular.

Moreover, in order to obtain a more realistic channel model, recent works have introduced a new modeling approach based on ray tracing [42, 43]. The proposed approach is based on an innovative use of Zemax®; a commercially available optical and illumination design software [44]. A three-dimensional

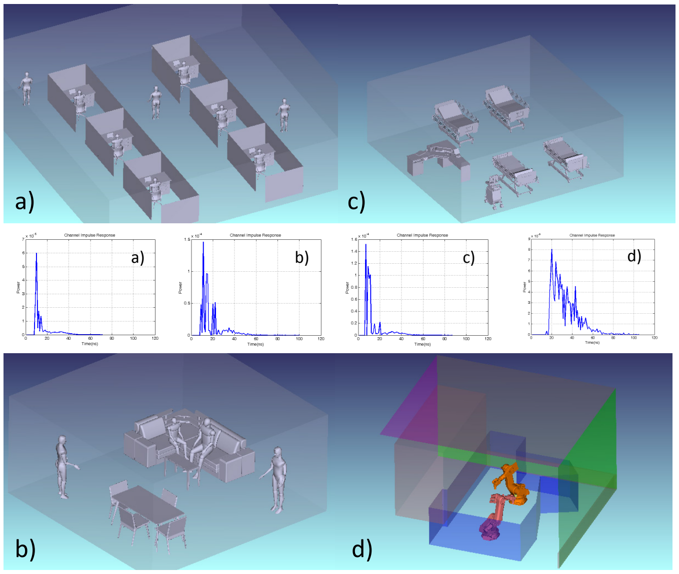

Fig. 6. The proposed LiFi channel models cover selected use cases: a) office with cubicles, b) home, c) hospital, d) manufacturing. Selected impulse responses are shown in the middle. OPTICWISE makes all data sets publicly available.

simulation environment is created where the geometry of the indoor environment, the reflection characteristics of the surface materials and the specifications of the light sources and detectors are specified. The computer aided design (CAD) objects can be further imported to model furniture and any other objects within the indoor environment.

Zemax® also allows defining the wavelength-dependent reflectance for each surface material. For light sources, commercially available LEDs can be used which are readily available in radiant source models (RSMs) database. The RSM file for a light source contains the measured radiant or luminous intensity of the source as a function of wavelength, position, and angle. As such, it can be accurately used to characterize the behavior of the source in both the near- and far-fields. For a given number of rays and the number of reflections, the non-sequential ray tracing of Zemax® calculates the detected optical power and path lengths from source to detector for each ray in the specified environment. This information is then imported into Matlab® and the corresponding optical CIR is obtained from the time-of-flight distribution of the power received from all detected paths.

In this way, channel models for specific scenarios have been obtained that are proposed by OPTICWISE in the IEEE 802.15.7r1 working group. Four environments (see Fig. 6) are considered so far [45], representing selected use cases described in Section III. CIRs, channel DC gains and RMS delay spreads can be found in [45].

In the office scenario, a room size of $(14 \times 14 \times 3)\ \mathrm{m}^3$ is considered. Walls and ceiling are assumed to be plaster while the floor is pinewood. 32 LED luminaries (Cree LR24-38SKA35) are used, see [46]. An uniformity of illumination equal to 0.5211 is achieved. Minor effects of objects in the room on the CIRs can be observed in [45].

In the home scenario, a living room of size $(6 \times 6 \times 3)\ \mathrm{m}^3$ is used with table, chairs, couch and coffee table. 9 LED luminaries (Cree CR6-800L) are used. An uniformity of illumination equal to 0.9068 i achieved. DC gain is higher and RMS delay spread smaller than in the office.

In the hospital scenario, an emergency room of size $(8 \times 8 \times 3)\ \mathrm{m}^3$ is considered with four beds, reception desk and several diagnostic instruments. 16 LED luminaries (Cree CR14-40L-HE) are used to reach an uniformity of illumination equal to 0.5930. RMS delay spread in the hospital is smaller than in the office but larger than in the home, which is obviously related to the room size.

In the manufacturing scenario, a real setup was taken over from car production. In the factory hall, which is 6.8 m high, outer walls cover an area of $(9.2 \times 8)\ \mathrm{m}^2$. For protection, a 1 m high folding screen is used. It is made of metal and glass, surrounding two robots. 6 transmitters are located at the head of one robot, arranged on the six sides of a cube, to achieve omnidirectional coverage. 8 receivers are located at different positions on top of the folding screen. Long delays are observed, due to the metallic objects and the large room size, in particular if 6 transmitters are used together and the LOS to a receiver is blocked. Fortunately, the LOS is free to some other receivers, so that a robust optical wireless communications link can always be established.

There is severe time dispersion, in particular in NLOS scenarios with multipaths delayed by tens of nanoseconds. The dispersion is partly due to the fact that multiple LEDs are operated together. Moreover, reflected signals are noticeable.

VI. Conclusions and Way Forward

This paper presented a European perspective - authors are members of the European COST 1101 research network OPTICWISE - on the ongoing developments towards a next generation optical wireless communication standard. OPTICWISE is an Associate Member of the European 5G public-private partnership (PPP) and proposed LiFi is as a candidate techology for 5G. The IEEE 802.15 working group was found appropriated for the bottom-up development started by academics and research institutes, already including small and medium enterprises, towards realizing the LiFi concept.

A revision of the IEEE 802.15.7-2011 standard for visible light communication is now prepared denoted as 802.15.7r1. While the revision addresses low data rate communication based on imaging sensors, it also offers an opportunity to establish high data-rate mobile communications, based on an optical wireless standard. OPTICWISE is actively contributing to 802.15.7r1. Members proposed the use cases and main features of LiFi and provided the channel model. The ongoing work towards the standard is of course open to any other contributors at any time.

VII. Acknowledgements

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