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OFCOM-Report

Light Fidelity (LiFi)

Executive Summary

The term LiFi denotes "light fidelity" and it is a form of bidirectional, networked, mobile, and high-speed wireless communications closely equivalent to Wireless Fidelity (WiFi) [1]. Unlike WiFi, the technology uses visible light spectrum instead of the increasingly congested radio frequency (RF) spectrum. Similarly to WiFi, this technology allows connection of different web-enabled devices such as computers, smart TVs, smart phones, etc. to internet; provides the inter-connection of WiFi enabled things such as refrigerators, watches, cameras, etc. in Internet of Things (IoT); and makes off-loading from cellular networks possible, addressing this way capacity needs for mobile broadband connections (Fig. 1). In addition, LiFi has a huge amount of visible light spectrum that is unregulated and does not require licenses. It has to be ensured, however, that LiFi systems do not present any health hazards and that they are properly installed so as not to create any electromagnetic interference.

According to recent market research predictions, LiFi technology is expected to reach the market value of 8,500 Million USD by 2020 [2]. Nowadays, there are several commercial products and a few product prototypes that seem to be in their final stages before appearing on the market. The technology seems promising and even National Aeronautics and Space Administration (NASA) recently announced plans to study LiFi's potential uses in space travel [3]. LiFi technology offers numerous benefits, however, there are still important challenges that must be overcome before it becomes a ubiquitous part of everyday wireless communications.

In this report, we give an overview of the LiFi technology, discuss its benefits and challenges, and summarize research and standardization activities in the field, including commercially available products.

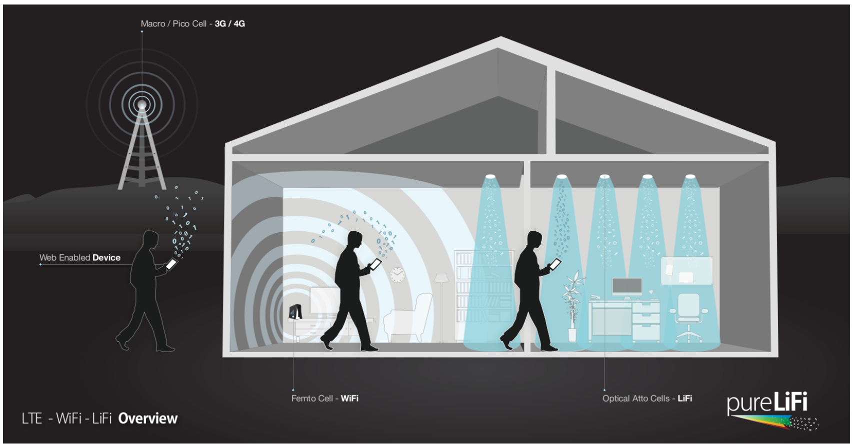

Figure 1: LiFi works in complement with existing and emerging wireless systems [4].

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1 LiFi Technology

A typical indoor LiFi system link is illustrated in Fig. 2 [4]. It consists of a light source, line-of-sight (LOS) propagation medium, and a light detector. Information (streaming content), in the form of digital or analog signals, is input to electronic circuitry that modulates the light source. The source output passes through an optical system (to control the emitted radiation, e.g., to ensure that the transmitter is eye safe) into the free space. The received signal comes through an optical system (e.g., an optical filter that rejects optical noise, a lens system or concentrator that focuses light on the detector), passes through the photo diode (PD), and the resulting photo-current is amplified before the signal processing electronics transforms it back to the received data stream [13].

For most indoor applications, light emitting diodes (LEDs) are the favored light sources due to the relaxed safety regulations, low cost, and energy efficiency [13]. They are replacing incandescent bulbs as the primary source of illumination in residential and public environments and by as early as 2018, the majority of new energy-efficient lighting installations are expected to be LED-based [14]. For higher speeds or longer distances, laser diodes appear to be a better choice.

The brightness of LEDs can be modulated at a high rate, which enables the combination of both illumination and wireless communication [15, 16]. LEDs emit incoherent light that has different wavelengths and phase (unlike the coherent light of laser diodes), hence, simple and low-cost Intensity Modulation (IM) is performed, where the transmitted signal is modulated into the instantaneous optical power of the LED. Since IM changes instantaneous power of the LED, Direct Detection (DD) is the only feasible demodulation method that converts the incident optical signal power into a proportional current. The setup is far simpler and less expensive than coherent detection chains used in RF, where a local oscillator is used to extract the base-band signal from the carrier. Modulation frequencies are kept high enough to avoid flicker in the emitted light, so that the modulation is imperceptible by human eye [12, 15].

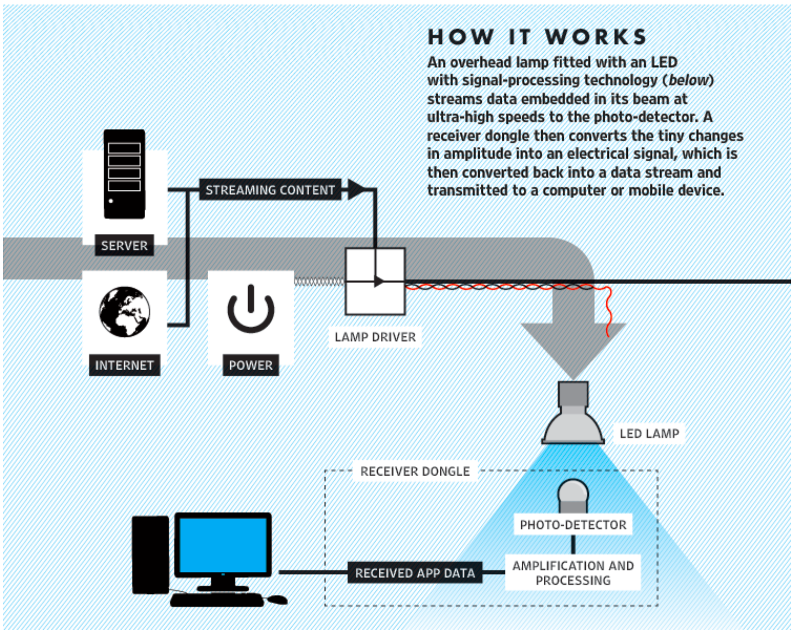

Figure 2: General LiFi link [4].

There are generally two types of photo detectors that can be used in LiFi systems: PIN photo diodes and Avalanche photo diodes (APDs). Although the APD have a higher gain, the PIN PDs have been predominantly used due to high temperature tolerance, lower cost, performing better in scenarios where the receiver gets flooded with relatively high intensity light [12].

In order to provide internet access, an uplink from the device to the network needs also to be ensured in addition to the downlink, which will allow the device to request, modify, and upload information. An example of bidirectional (duplex) LiFi communication system is shown in Fig. 3. LED-PD pairs need to be placed on both ends of the wireless communication link to provide this functionality [5].

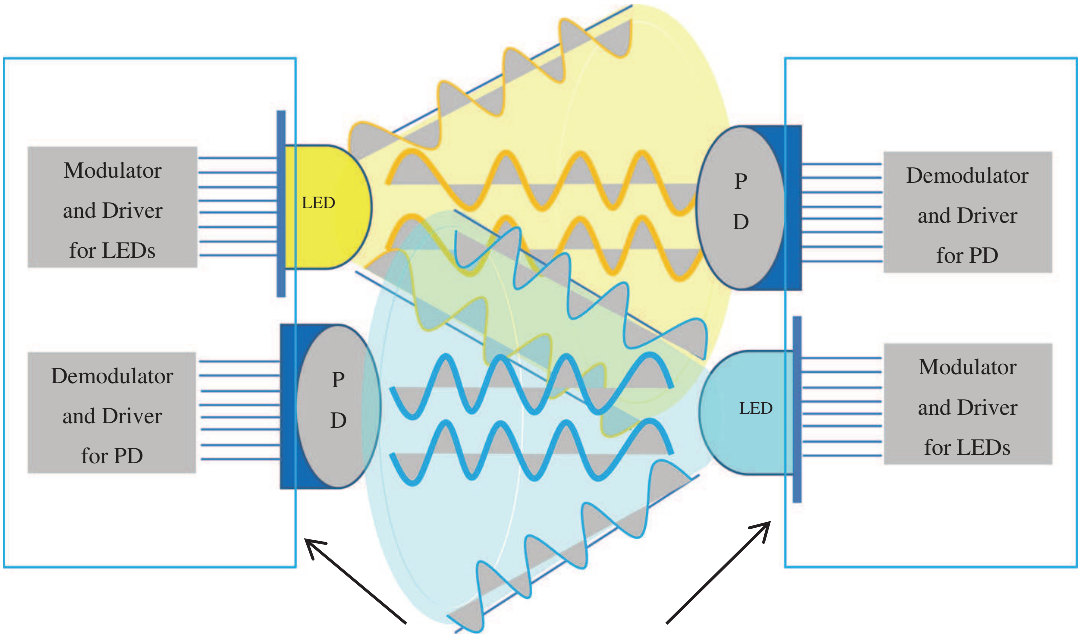

Figure 3: Basic concept of LiFi duplex communication [5].

Due to the inherent directionality of light (as opposed to RF signals), any space that is to be illuminated needs several light fixtures to sufficiently cover the area. Since in a LiFi network, every light source is a wireless access point, it is essential for network operation that the communication link remains unbroken while a user is moving. Hence, the network must *hand-over* the user from one access point to the next (see Fig. 1). Additionally, if a given area hosting several users/devices is illuminated by a single luminaire, LiFi will necessitate sharing of time and frequency resources by providing *multiple access*.

2 Benefits and Advantages of LiFi vs. RF Communications

Recently, communication by visible light has been gaining popularity as a complement to RF communications due to the following advantageous features (see also Table 1):

- **RF Congestion and Capacity Crunch:** The RF spectrum is a natural resource of the state and its usage is regulated to mitigate interference and pollution and to ensure its efficient usage. According to Cisco predictions [6], overall mobile data traffic is expected to grow to 49 exabytes[1] per month by 2021, which amounts to a sevenfold increase over 2016 (Fig. 4). According to the same report, mobile off-load will increase from 60 percent (10.7 exabytes/month) in 2016 to 63 percent (83.6 exabytes/month) by 2021. The demand for broadband wireless data access is constantly increasing and the radio frequency spectrum, that is limited and for the most part licensed, is becoming progressively more congested.

  On the other hand, the visible light spectrum is unlicensed and currently largely unused for communications. Moreover, potential bandwidth of visible light ($\sim$ 400 THz to $\sim$ 780 THz) is thousand times wider than the conventional RF bandwidth ($\sim$ 3 kHz to $\sim$ 300 GHz). As a result, LiFi system have huge amount of available unregulated spectrum to complement short-range wireless-transmission and to potentially alleviate the RF spectrum congestion, that is especially apparent in the 2.4-GHz Industrial, Scientific, and Medical (ISM) band [15]. With 12 billion light bulbs around the world with unlicensed, reusable bandwidth, there can be potentially as many LiFi transmitters and access points [12].

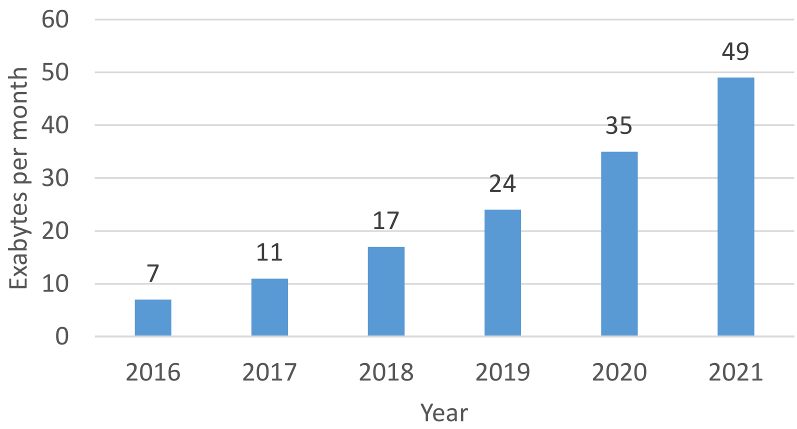

Figure 4: Cisco forecasts 49 exabytes per month of mobile data traffic by 2021 [6].

- **Spatial Reuse:** Since visible light does not penetrate through building walls or other opaque materials and can be directed to the desired working area, LiFi can exhibit a high degree of spatial reuse. LiFi signals in adjacent areas, rooms, or apartment units would not interfere with each other, thereby potentially admitting a far higher spatial density of communication rates than it is achievable with RF.

- **Security:** RF waves pass through walls and are susceptible to eavesdropping. An intruder or hacker outside a building can tap into the WiFi data communications of computers inside the building. With the confinement property of visible light, on the other hand, there are well defined coverage zones that enhance communication security by preventing eavesdropping from outside of a room, apartment, or building. Although, some recent research has shown the feasibility of eavesdropping using the light signals leaked through the gap between floor and door, keyhole and even partially covered windows [17].

- **Electromagnetic Interference (EMI):** Radio waves create EMI that can impair normal operation of electrical instruments and equipment in airplanes and hospitals, and is especially dangerous in hazardous industrial zones, such as power/nuclear generation or oil and gas drilling. LiFi uses light instead of radio waves, which is intrinsically safe and does not create EMI. It is important to

[1] 1 exabyte = 1000 terabytes

note, however, that recent measurements by European Broadcasting Union (EBU) have shown EMI coming from incorrectly installed LED lamps [18]. Original transformers will no more comply with electromagnetic compatibility limits if full-load halogen lamps are simply replaced by low-load LED lamps as harmonics of the switching frequency of the transformer under low-load conditions can occur across the entire RF spectrum. Therefore, frequency limits of the lighting emissions standard CISPR 15 may need to be extended to beyond the present 300 MHz.

- **Safety:** In illumination conditions, in principle, there are no health hazards of visible light. Studies have shown some health concerns relating to flicker that may induce biological human response (photosensitive epilepsy) [19, 20]. Moreover, glare of certain blue-rich LED designs is thought to have psychological effects such as disrupting people’s sleep patterns and harming nocturnal animals [21].
- **Multipath:** At frequencies of the visible light, constructive and destructive interference occur on a micron scale and get averaged by the receiver that is thousand times greater in size. Therefore, LiFi exhibits no fading caused by multipath propagation or Doppler shift.
- **Complexity:** Due to the fact that LiFi is a non-coherent mode of communication, the front-end components of both transmitters and receivers are relatively simple and cheap devices that operate in the baseband and do not require frequency mixers or sophisticated algorithms for the correction of RF impairments such as phase noise and IQ imbalance.
- **Existing Infrastructure:** LiFi can be implemented into existing lighting infrastructure with the addition of a few relatively simple and low-cost front-end components operating in baseband.
- **Energy Efficiency:** LiFi is combined with LED illumination. Since LEDs are energy efficient and highly controllable light sources, LiFi belongs to eco-friendly green communication technology.
- **Accurate Indoor Positioning:** RF based positioning schemes cannot provide sub-meter accuracy. The LiFi provides a promising way to perform accurate (centimeter-level) indoor positioning of mobile devices due to the high directivity of visible light.

Table 1: Comparison of LiFi and RF Communication (adapted from [12])

Parameter	**RF**	**LiFi**
Spectrum	$\sim$ 300 GHz (licensed)	$\sim$ 400 THz (unlicensed)
Security	Limited	High
EMI	Yes	No
Safety	Intensity regulated	Unregulated
Coverage	Wide	Limited
Multipath	Yes	No
Complexity	High	Low
Infrastructure	Access point	Illumination
Power consumption	Medium	Low (combined with LED illumination)

3 Challenges and Limitations of LiFi

Despite having inherent advantages compared to RF communication systems, LiFi still faces numerous challenges and limitations that need to be addressed so that it can be deployed in practice as a high-speed mobile networking technology. A non-exhaustive list of these shortcomings is given in what follows.

- **Uplink:** Providing an efficient uplink scheme for LiFi (from photo diode to LED luminaire) has been challenging, as LiFi with illumination has predominantly broadcast characteristics. A visible light uplink would be inefficient for portable devices which run on low power and may also be considered inconvenient or unpleasant. To address this challenge, use of other types of communication has been proposed and investigated, where RF or infrared can be used for transmitting uplink data. Utilizing different technologies for uplink and downlink, however, gives rise to HetNets that impose additional practical challenges such as complex network management and reliable data recovery [17].
- **LED Modulation Bandwidth:** The data rate of the LiFi link is limited by the modulation bandwidth of high brightness LEDs used in light fixtures and lamps. Due to the power-bandwidth trade-off of LEDs and the various parasitic impedances in the LED packaging, signals modulated at high frequencies are strongly attenuated [15]. If the entire white spectrum is used at detection, the modulation bandwidth is limited to $\sim$ 2.5 MHz. Blue filtering enhances the modulation bandwidth up to $\sim$ 20 MHz [12]. High data rates over such a limited bandwidth can only be achieved by exploiting high Signal-to-Noise Ratios (SNRs) with high-order modulation techniques; using arrays of smaller, less powerful LEDs (with lower internal parasitic impedances); or using Wavelength Division Multiplex (WDM) to transmit independent data streams on differently colored LEDs that combine to make white light [15]. Ultimately, off-the-shelf laser diodes (LDs) may be used [22].
- **Coverage/Shadowing/Mobility:** The transmission distance of visible light sources is limited and requires LOS for best SNR conditions to achieve high data rates. With an object or human blocking the LOS, the observed optical power degrades resulting in severe data rate reductions. User mobility thus introduces novel issues for LiFi as the SNR varies dramatically when the user moves within the cell. This effect may be minimized by distributing lighting sources so that high SNR is maintained throughout the cell [12, 17].
- **Light Interference:** Other artificial and natural light sources create interference and act as unmodulated sources at the receiver. This interference increases shot noise[2] and if high enough can cause receiver saturation. Filtering can be used as a mitigation technique here to remove a significant portion of the shot noise [12].
- **Lights Off Mode:** LiFi applications based on LED lighting are more attractive in environments where the lights are always switched on, for instance, in industrial settings, public transport, or medical areas. Some low data rate transmission can be achieved by making the light emitted to be low enough so that human eyes perceive it as being switched off [23]. Integration of infrared LED chips into future LED luminaires would allow for continuous data flows when the lights are switched off [12, 14].
- **Backhaul Integration:** LEDs need to be connected to internet and their deployment is very dense. Therefore, the cost of implementing wired infrastructure (such as Ethernet, fiber, etc.) as backhaul can be very high. Given that LED fixtures and lamps are connected to the alternating current (AC) power line, a natural choice for the backhaul technology is powerline communication (PLC). Even though the cost of cable deployment is alleviated in this case, the use of PLCs incurs cost overheads of using Ethernet-to-power modem and power-to-LiFi modems. In addition, the implemented backhaul technology needs to provide high data rates especially in the cases in which multiple mobile devices are to be served by the same LiFi network [12, 15, 17].
- **Commercialization:** There are certain business challenges facing widespread adoption of LiFi in the consumer market. For integrating downlink, for example, two different industries need to work together. One is the lighting manufacturers who need to make appropriate modifications to their lamp and fixture designs. The other are mobile device manufacturers who need to install high-speed photo-diode receivers in their devices. From the lighting manufacturers’ perspective,

[2] Shot noise originates from the particle nature of light and describes the fluctuations of the number of photons detected.

the extremely high lifetime of LEDs may initially cause a high revenue in LED sales but later on lead to ‘socket saturation.’ On the other hand, integrating a new hardware into the existing devices may lead to unnecessary increase in cost and change in robustness of design for mobile device manufacturers [12, 15].

4 University and Research Activities

In this section, we give a non-exhaustive overview of university and research groups that have been active in the area of LiFi. The reported characteristics (such as data rates) are demonstrated in laboratory settings with prototypes and proof-of-concept solutions.

- Researchers at the University of Oxford have reached a new milestone in networking by using LiFi with bidirectional speeds of 224 Gbps. The link operates over $\sim$ 3 m range at 224 Gbps (6×37.4 Gbps) and 112 Gbps (3×37.4 Gbps) with a wide field of view (FOV) of 60^o and 36^o, respectively. This is the first demonstration of a wireless link of this type with a FOV that offers practical room-scale coverage [24].
- Researchers from Fraunhofer Heinrich Hertz Institute in Berlin, Germany, have recently demonstrated a bidirectional real-time visible light prototype entirely based on commercially available low-cost hardware, supporting adaptive data rates according to the lighting conditions. At a typical working distance of 2 m between the ceiling and the tabletop, and in a circular spot covering a typical working area of roughly 60 cm in diameter, the system enables a data rate of 200 Mbps per user. By using the same transceiver combined with narrow-beam optics, the system could achieve 100 Mbps over 20 m distances. By reducing the distance, the peak data rate of 500 Mbps was reached [14].
- Researchers from the University of Edinburgh study the communication properties of off-the-shelf visible light laser diodes [22]. Compared with off-the-shelf LEDs and even compared with the fast μLEDs, laser diodes exhibit modulation speeds which are at least an order of magnitude higher. At the same time, the output efficiency of LDs is high enough to support a coverage of 1 m^2 at a distance of 2.88 m and at an achievable data rate of 3.43 Gbps for a single RGB triplet of LDs. When simultaneous wireless connectivity and illumination are realized with such RGB LDs, the achievable data rate in well-illuminated areas is approximately 14 Gbps. Using WDM with 36 parallel streams, for example, is expected to deliver data rates of over 100 Gbps at standard illumination levels.
- Disney Research in Zürich has demonstrated a low-data-rate device-to-device communication system called EnLighting [7]. The system is based on LED light bulbs enhanced with photo diodes and microcontrollers (Fig. 5). They are Linux programmable and can both send and receive providing this way communication with objects in a room as well as with other light bulbs nearby. EnLighting supports low-data-rate (up to 600 bps) communication services in a room (and via a gateway, beyond the room), which gives the basis for other applications, e.g., a location service.

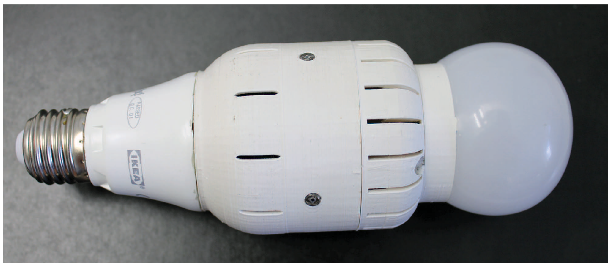

Figure 5: LED light bulb transceiver from Disney Research [7].

- Researchers from several different universities and institutes are working on coexistence between WiFi and LiFi. In their recent paper [8] they demonstrate that a close integration of both technologies enables off-loading opportunities for the WiFi network and serving more mobile users, while the stationary users will preferably be served by LiFi (Fig. 6). They have demonstrated by proof-of-concept results, using state-of-the-art LiFi and WiFi frontends, that both technologies together can more than *triple* the throughput for individual users and yield a solution that can adequately address the need for enhanced indoor coverage with the highest data rates required in the fifth generation of mobile networks (5G).

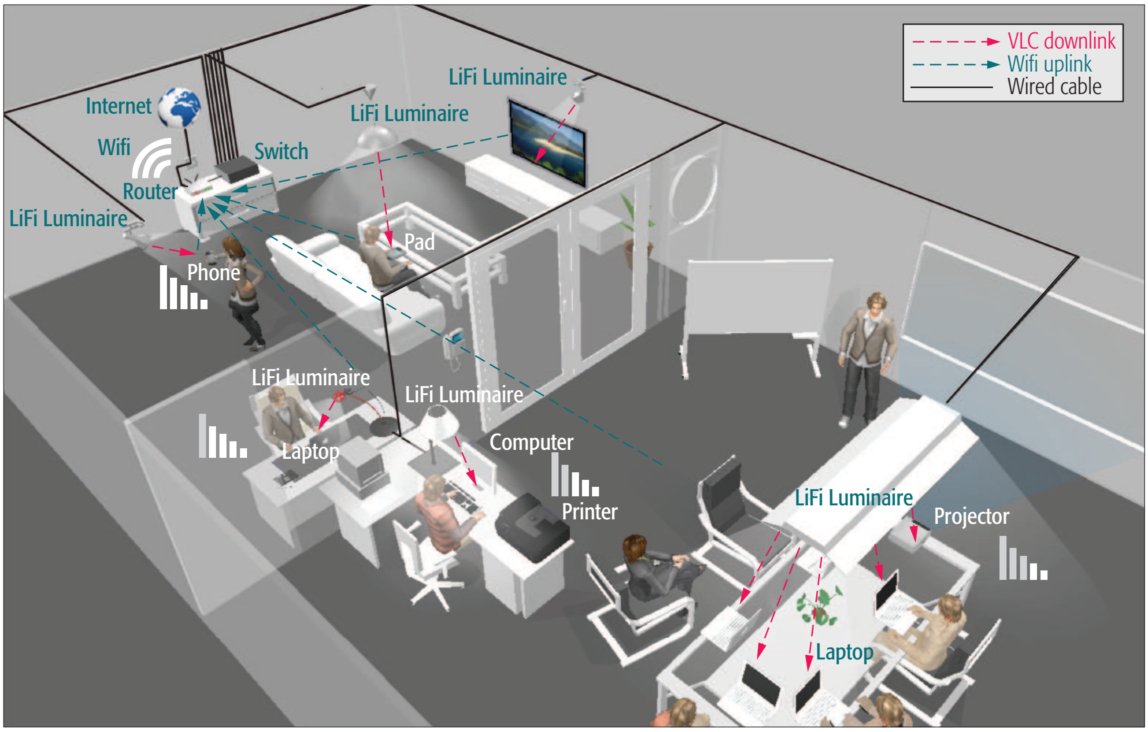

Figure 6: The proposed LiFi+WiFi HetNet [8].

5 Standardization Activities

Standardization activities on LiFi technology are ongoing within the Institute of Electrical and Electronics Engineers (IEEE) 802.15.7 standard that accommodates infrared and near ultraviolet wavelengths, in addition to visible light, to add options such as:

- Optical Camera Communications, which enable scalable data rate, positioning/localization, and message broadcasting, using devices such as the flash, display, and image sensor as the transmitting and receiving devices.
- LED-ID which is wireless light ID (Identification) system using various LEDs.
- LiFi which is high-speed, bidirectional, networked, and mobile wireless communications using light.

A first draft of the standard IEEE P802.15.7r1 is expected near the end of 2016 and the final version near the end of 2017 [25].

Members of the European COST 1101 research network OPTICWISE [26] are actively contributing to 802.15.7r1. They proposed the use cases (Fig. 7), the main features of LiFi, and provided the channel model [9].

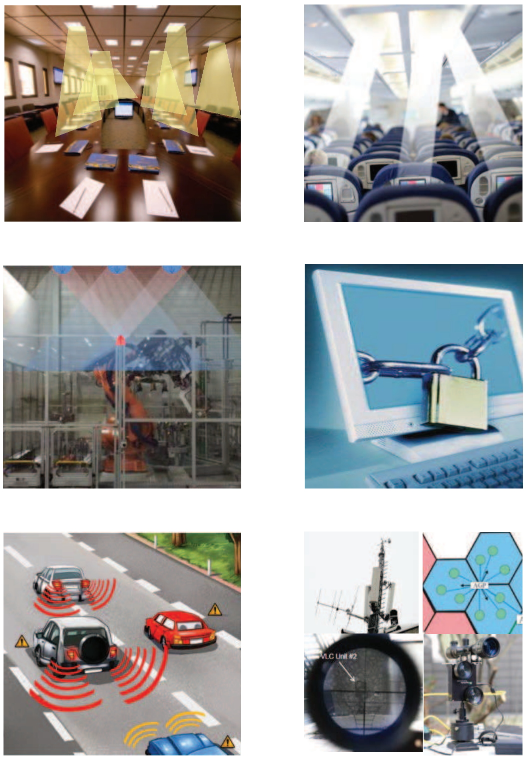

Figure 7: Exemplary LiFi use cases: Conference room (top left), Aircraft cabin (top right), Industrial scenario (center left), Secure wireless scenario (center right), Vehicle-to-vehicle communication (bottom left), Wireless Backhaul (bottom right) [9].

In November 2016, IEEE has formed a Topic Interest Group (TIG) to start activities of LiFi standardization within the IEEE wireless LAN Standard P802.11. The group is lead by pureLiFi [4] and has many supporting institutions (a non exhaustive list includes Cisco, LG Electronics, Lucibel, Schneider, Nokia, Boeing, Hewlett Packard, and Fraunhofer).

International Telecommunication Union (ITU) SG15 started studying indoor high-speed visual light communication systems (100 Mbps to 1 Gbps), including general characteristics, wavelength band plan, architecture, interfaces and protocols. The work is in a very early stage.

ITU SG1, WP1A has started working on a report on spectrum management in visible light communications. This report is also in a very early drafting stage.

6 Products and Prototypes

pureLiFi [4]

pureLiFi is a start-up company founded in 2012 by Prof. Haas of the University of Edinburgh to market visual light communication technology after four years of extensive research. The company first developed a ceiling unit called Li-Flame capable of 10 Mbps downlink and 10 Mbps uplink communication with a range of up to 3 m using standard LED light fixtures. pureLiFi has now evolved the Li-Flame into the LiFi-X, a new generation of drivers and receivers that were introduced at the 2016 Mobile World Congress in February. LiFi-X (see Fig. 8) provides an access point that connects to any LiFi enabled LED light. It offers full duplex communication with a 40 Mbps downlink and 40 Mbps uplink as well as full mobility and multiple users per LiFi Access Point.

Figure 8: LiFi-X was introduced at Mobile World Congress 2016 by pureLiFi [4].

Lucibel [10]

pureLiFi and Lucibel, a French company that specializes in the design of new-generation lighting solutions based on the LED technology, have developed and are in the process of marketing Europe’s first, fully industrialized LiFi luminaire: Ores LiFi [10]. The Lucibel LiFi solution enables the deployment of a full wireless network through a bidirectional line rate up to 42 Mbps. The Lucibel LiFi system offers high-speed mobile connectivity within a network while supporting multiple access and the “handover.” Each LiFi luminaire can simultaneously serve multiple (up to eight) LiFi stations (Fig. 9). The implemented handover functionality allows users to keep automatically a stable connection from one luminaire to another.

The LiFi luminaire and USB key will be exclusively manufactured by Lucibel in France at its industrial site in Barentin (Normandy).

Sogeprom, major property developer subsidiary of Société Générale Group, was the first user to test the LiFi high bandwidth in its Parisian premises by installing the first Lucibel prototype.

Microsoft is also implementing the LiFi solution at its innovation center in Issy-les-Moulineaux in order to to provide the next generation of wireless connectivity for its customers.

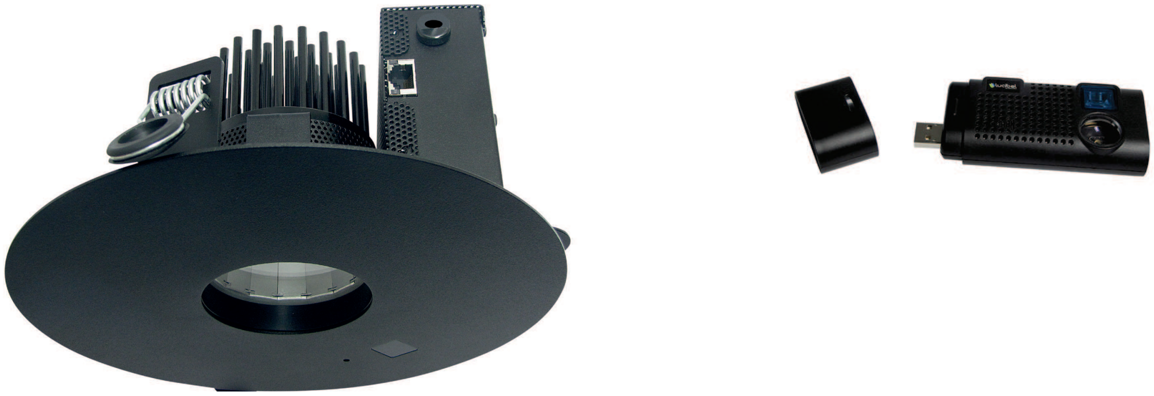

Figure 9: Lucibel LiFi luminaire (left) and LiFi USB key dongle (right) [10].

SLUX [27]

SLUX is a Swiss company that has developed a Li-Bluetooth system for data transfer by visible light. The company specializes in solutions that use reflected signals, without a need of having a direct LOS path between the transmitter and receiver. They report data rates as high as 15 Mbps in duplex mode. The company also developed a light-transmitting wireless headphones, the second prototype of which has been completed in 2016.

LUCIOM [11]

LUCIOM is a French start-up company created in October 2012. The company has several products in their portfolio

- Geo VLC: low bandwidth transmitter/receiver kits for indoor location (with prices ranging from 60 to 550 EUR per unit, depending on the functionality)
- High data rate solutions with LED LiFi internet transmitters and USB LiFi/infrared dongles providing data rates of 20 Mbps (downlink) and 5 Mbps (uplink) and with unit prices starting from 2,200 EUR (Fig. 10).

basic6 [28]

Basic6 is a start-up company founded in the USA developing an indoor positioning system GeoLiFi, which uses a store’s lighting infrastructure to anonymously deliver proximity messaging, information about products, related promotions, and visual shopping lists to customers and employees. At the same time, the solution provides the retailer with detailed analytics of such metrics as customer and employee engagement rates as well as store and department dwell times. The company works on software and actively partners with other lighting companies that provide hardware for LiFi (such as OLEDCOMM [29] a French start-up company of the University of Versailles Saint-Quentin-en-Yvelines).

Velmenni [30]

Velmenni is an Estonian start-up company that had successful trials of the LiFi technology in various offices and industrial environment in Tallinn, Estonia and are presently doing numerous pilot projects to utilize Visible Light Communication in diverse industrial contexts (in collaboration with Airbus to test the technology on the airplanes). The prototype consists of a LED transceiver and an external photodetector receiver that is connected to a laptop via USB. The system works in duplex regime (uplink and

Figure 10: LUCIOM’s “Ready to Use” solution [11].

downlink) and the reported data rates go as fast as 1 Gbps. The demonstrated distances between Tx-Rx are several tens of cm. However, it will take some years before the prototype becomes a commercial product.

Fraunhofer Institute LiFi Hotspot [31]

The LiFi Hotspot developed at Fraunhofer IPMS allows for the installation of a private, high-speed network without imposing cables. The system offers high data rates of up to 1 Gbps, over a distance of up to 30 m and its small size is easily aligned and inexpensive to install. In addition to LiFi broadcasting modules sending data in one direction, technology developed at Fraunhofer IPMS offers the possibility of a real-time capable and bidirectional, “full duplex” communication. A prototype has been installed in a conference room on Mainau island (Constance lake).

LVX System [32]

LVX System is a US company based in Kennedy Space Center with a patented technology offering high-quality LED light systems that also securely stream high-speed data. They have recently signed a Space Act Agreement with NASA [3] .

7 Outlook

According to a new market research report published by Markets and Markets in 2015, LiFi technology is expected to reach a market value of 8,500 Million USD by 2020 [2]. Nowadays, there are several products and few product prototypes that seem to be in their final stages before appearing on the market.

The technology seems promising and many major key players are considering it. Microsoft is implementing the Lucibel's LiFi solution at its innovation center in France. NASA recently announced plans to study LiFi's potential uses aboard spacecraft to improve the safety, comfort, and quality of life for future astronauts. European Space Agency (ESA) has been using laser links for communication between Low Earth Orbit (LEO) satellites [33]. There have been news reports that Apple is experimenting with LiFi wireless data for future iPhones and iPads [34].

The LiFi technology uses unregulated spectrum of visible light that does not need licensing. It has to be ensured, however, that the LiFi systems do not pose any health hazards (photosensitive epilepsy or psychological effects of the LED colors) and that they are correctly installed so that they do not produce any EMI.

Although LiFi technology does offer numerous benefits, there are still important challenges that must be overcome before it becomes a ubiquitous part of everyday wireless communications.

References

[1] H. Haas and N. Serafimovski, “LiFi unlocking unprecedented wireless pathways for our digital future,” *IEEE ComSoc Technology News*, Dec. 2016. [Online]. Available: http://www.comsoc.org/ctn/does-5g-have-bright-future-light-based-communications-wireless-solutions

[2] Markets and Markets. (2015) Free space optics (FSO) and visible light communication (Li-Fi) market by component, application (smart store, consumer electronics, defense, transportation, aviation, hospital, underwater, and hazardous environment), and by geography - Global forecast to 2020. [Online]. Available: http://www.marketsandmarkets.com/Market-Reports/visible-light-communication-market-946.html

[3] NASA. (2015). [Online]. Available: https://blogs.nasa.gov/kennedy/2015/07/30/partnership-may-lead-to-advanced-communication-technology/

[4] pureLiFi. (2016). [Online]. Available: http://purelifi.com/

[5] A. Kumar, A. Mihovska, S. Kyriazakos, and R. Prasad, “Visible light communications (VLC) for ambient assisted living,” *Wireless Personal Communications*, vol. 78, no. 3, pp. 1699–1717, 2014.

[6] Cisco, “Cisco Visual Networking Index (VNI) Update Global Mobile Data Traffic Forecast, 2016-2021,” Tech. Rep., 2017. [Online]. Available: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html

[7] S. Schmid, T. Richner, S. Mangold, and T. R. Gross, “EnLighting: An Indoor Visible Light Communication System Based on Networked Light Bulbs,” in *International Conference on Sensing, Communication and Networking (SECON)*, 2016, pp. 1–9.

[8] M. Ayyash, H. Elgala, A. Khreishah, V. Jungnickel, T. Little, S. Shao, M. Rahaim, D. Schulz, J. Hilt, and R. Freund, “Coexistence of WiFi and LiFi toward 5G: Concepts, opportunities, and challenges,” *IEEE Communications Magazine*, vol. 54, no. 2, pp. 64–71, 2016.

[9] V. Jungnickel, M. Uysal, N. Serafimovski, T. Baykas, D. O’Brien, E. Ciaramella, Z. Ghassemlooy, R. Green, H. Haas, P. A. Haigh, V. P. G. Jimenez, F. Miramirkhani, M. Wolf, and S. Zvanovec, “A European view on the next generation optical wireless communication standard,” in *IEEE Conference on Standards for Communications and Networking (CSCN)*, Oct 2015, pp. 106–111.

[10] LiFi by Lucibel. (2016). [Online]. Available: http://www.lucibel.com/lifi-haut-debit/

[11] LUCIOM. (2016). [Online]. Available: http://luciom.com/

[12] D. Karunatilaka, F. Zafar, V. Kalavally, and R. Parthiban, “LED based indoor visible light communications: State of the art,” *IEEE Communications Surveys Tutorials*, vol. 17, no. 3, pp. 1649–1678, 2015.

[13] H. Elgala, R. Mesleh, and H. Haas, “Indoor optical wireless communication: Potential and state-of-the-art,” *IEEE Communications Magazine*, vol. 49, no. 9, pp. 56–62, 2011.

[14] L. Grobe and A. Paraskevopoulos, “High-speed visible light communication systems,” *IEEE Communications Magazine*, pp. 60–66, Dec. 2013.

[15] A. Jovicic, J. Li, and T. Richardson, “Visible light communication: Opportunities, challenges and the path to market,” *IEEE Communications Magazine*, vol. 51, no. 12, pp. 26–32, 2013.

[16] G. Corbellini, K. Akşit, S. Schmid, S. Mangold, and T. R. Gross, “Connecting networks of toys and smartphones with visible light communication,” *IEEE Communications Magazine*, vol. 52, no. 7, pp. 72–78, 2014.

[17] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, “Visible light communication, networking, and sensing: A survey, potential and challenges,” *IEEE Communications Surveys and Tutorials*, vol. 17, no. 4, pp. 2047–2077, 2015.

[18] EBU, “LED Lighting Interference,” 2014. [Online]. Available: https://tech.ebu.ch/docs/factsheets/ebu_tech_fs_ledinterference.pdf

[19] A. Wilkins, J. Veitch, and B. Lehman, “LED lighting flicker and potential health concerns: IEEE standard PAR1789 update,” *2010 IEEE Energy Conversion Congress and Exposition, ECCE 2010 - Proceedings*, pp. 171–178, 2010.

[20] A. J. Wilkins, “Designing to mitigate the effects of flicker reducing risks to health and safety,” *IEEE Power Electronics Magazine*, pp. 18–26, September 2014.

[21] J. Hecht, “LED streetlights are giving neighborhoods the blues,” *IEEE Spectrum*, pp. 1–7, Oct. 2016. [Online]. Available: http://spectrum.ieee.org/green-tech/conservation/led-streetlights-are-giving-neighborhoods-the-blues

[22] D. Tsonev, S. Videv, and H. Haas, “Towards a 100 Gb/s visible light wireless access network,” *Optics Express*, vol. 23, no. 2, p. 1627, 2015.

[23] Z. Tian, K. Wright, and X. Zhou, “The DarkLight rises : Visible light communication in the dark,” in *Proceedings of the 22nd Annual International Conference on Mobile Computing and Networking. ACM, 2016*, 2016, pp. 2–15.

[24] A. Gomez, K. Shi, C. Quintana, M. Sato, G. Faulkner, B. C. Thomsen, and D. O’Brien, “Beyond 100-Gb/s indoor wide field-of-view optical wireless communications,” *IEEE Photonics Technology Letters*, vol. 27, no. 4, pp. 367–370, Feb 2015.

[25] IEEE TG7r1. (2016) IEEE 802.15 Working Group for WPAN. [Online]. Available: http://www.ieee802.org/15/

[26] ICT COST Action IC1101. (2015) OPTICWISE. [Online]. Available: http://www.cost.eu/COST_Actions/ict/IC1101

[27] SLUX: pursuit of perfection with light. (2017). [Online]. Available: https://www.slux.guru/

[28] basic6. (2016). [Online]. Available: http://www.basic6.com/

[29] oledcomm. (2014). [Online]. Available: http://www.entreprises.cci-paris-idf.fr/web/cci78/oledcomm

[30] Velmenni. (2016). [Online]. Available: http://velmenni.com/

[31] Fraunhofer Institute, “Li-Fi – Optical Wireless Communication,” Fraunhofer Institute for Photonic Microsystems, Dresden, Germany, Tech. Rep., 2016. [Online]. Available: http://www.ipms.fraunhofer.de/content/dam/ipms/common/products/WMS/WMS_OWC_2016_web.pdf

[32] LVX System. (2016). [Online]. Available: http://www.lvxsystem.com/index.php

[33] European Space Agency. (2016) Optical communication. [Online]. Available: http://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/Alphasat/Optical_Communication

[34] Apple Insider. (2016). [Online]. Available: http://appleinsider.com/articles/16/01/18/ios-code-shows-apple-experimenting-with-ultra-fast-light-based-li-fi-wireless-data-for-future-iphones

Abbreviations

5G fifth generation of mobile networks

AC alternating current
APD avalanche photo diode

DD Direct Detection

EBU European Broadcasting Union
EMI Electromagnetic Interference
ESA European Space Agency

FOV field of view

HetNet heterogeneous network

IEEE Institute of Electrical and Electronics Engineers
IM Intensity Modulation
IoT Internet of Things
ISM Industrial, Scientific, and Medical
ITU International Telecommunication Union

LD laser diode
LED light emitting diode
LEO Low Earth Orbit
LiFi Light Fidelity
LOS line-of-sight

NASA National Aeronautics and Space Administration

PD photo diode
PLC powerline communication

RF radio frequency

SNR Signal-to-Noise Ratio

USB universal serial bus

WDM Wavelength Division Multiplex
WiFi Wireless Fidelity