IEEE P802.11
Wireless LANs

|  |
| --- |
| Light Communications (LC) for 802.11: Use Cases and Functional Requirements: Guidelines for PAR and CSD Development |
| Date: 2017-06-26 |
| Author(s): |
| Name | Affiliation | Address | Phone | Email |
| Nikola Serafimovski | pureLiFi |  |  | nikola.serafimovski@purelifi.com |
| Dobroslav Tsonev | pureLiFi |  |  | dobroslav.tsonev@purelifi.com |
| Abdullah S. Nufaii | Saudi Aramco |  |  | abdullah.nufaii@aramco.com |
| Ahmed J. Ghamdi | Saudi Aramco |  |  | ahmad.ghamdi.54@aramco.com |
| Murat Uysal | Ozyegin University |  |  | murat.uysal@ozyegin.edu.tr |
| Vinko Erceg | Broadcom |  |  | vinko.erceg@broadcom.com |
| Tuncer Baykas | Istnabul Medipol University |  |  | tbaykas@ieee.org |
| Michael McInnis | Boeing |  |  | michael.d.mcinnis@boeing.com |
| Alphan Sahin | InterDigital, Inc. |  |  | alphan.sahin@interdigital.com  |
| Rui Yang | InterDigital, Inc. |  |  | rui.yang@interdigital.com  |
| Li Qiang | Huawei |  |  | john.liqiang@huawei.com  |
| Barnaby Fryer  | Co-op Group Ltd. |  |  | barnaby.fryer@coop.co.uk  |
| Volker Jungnickel | Fraunhofer HHI |  |  | volker.jungnickel@hhi.fraunhofer.de |

Abstract

This document contains the output of the Light Communications TIG, intended to describe the use cases, requirements, and technical feasibility of Light Communications in 802.11.

**Chair**

Nikola Serafimovski

**Editor**

Li Qiang

**Introduction**

We live in an increasingly connected world. The demand for mobile wireless communications is increasing at nearly 50% per year according to the Cisco Visual Networking Index.[32] This demand is expected to continue to increase as the Internet of Things (IoT) becomes a reality, and the number of connected devices grows from 5 billion to over 20 billion by 2020. Unsurprisingly, in 2016, over 50% of all wireless data went through a Wi-Fi access point. This enormous utilization results in a need for a continued increase in capacity of wireless networks, depending directly on the availability of additional unlicensed spectrum.

Undeniably, there are multiple solutions that can provide an increase in the available spectrum. WiGig solutions, defined in IEEE 802.11ad, .11mc, .11aj and 802.11ay are such examples. However, the continued deployment and growth of 802.11 technology relies on accessing further unlicensed spectrum based on the expected growth in the future. Besides, non-RF based solutions may be preferred for multiple complementary use-cases.

The light spectrum, for the most part, has been underutilised for communication. The visible light spectrum alone stretches from approximately 430 THz to 770 THz, which means that there is potentially more than 1000x the bandwidth of the entire RF spectrum of approx. 300 GHz. Both the visible light spectrum and the infrared spectrum are unlicensed. The TIG looks at the need and feasibility of expanding 802.11 protocols to efficiently access the light spectrum and satisfy various use-cases.

**Light Communications (LC) use cases**

1. Enterprise
	1. Data access: where network connections are based on LC for daily work, conference streaming remote desktops along with potential video, etc. Enhanced data security can be achieved for organizations that require high level of confidentiality. The directionality of light propagation can effectively reduce interferences in heavily populated offices. Wireless off-loading to light releases spectrum for connecting other devices.
	2. Use cases for RF sensitive facilities: for RF sensitive facilities such as hospital and mining, LC can provide safe data access where RF may not be allowed.
2. Home
	1. Data access: where mobile devices use LC for high data rate network access. Especially for heavily populated apartments so that reduced interference and enhanced privacy can be achieved.
	2. Home theater: Indoor use cases where high definition video and audio equipment connect to a LC AP
	3. Virtual reality (VR): use cases where VR goggles are connected to a LC AP
3. Retail
	1. Currently, delivery of high-bandwidth data at particular points in store requires cabled connection, makeing these spots immobile. Alteration of retail space to enable new customer experiences is a key part of retailer strategy. High-bandwidth flexible retail space through LC enables cost reductions for retailers when modifying or refitting the space.
	2. Data density of LC enables very-high bandwidth content without fear of interference with other wireless resources.
	3. Density of light fixtures and LC APs allows highly precise localisation of users and paths. This enables the provision of navigational directions for users within a store or mall.
	4. The fact that light is non-penetrative to opaque objects such as walls enables the establishment of very secure wireless signals.
4. IoT
	1. Home: smart home
		1. Connecting devices that convey sensitive information like CCTV cameras, baby monitors, etc. to a more private and secure LC network.
	2. Smart cities: provide high accuracy positioning
		1. LC AP can be installed on street furniture and ease congestion on spectrum resources by off-loading and releasing RF spectrum for increased connectivity of moving vehicles to the backbone.
	3. Factories of the future - Industrial and manufacturing
		1. In industrial and manufacturing scenarios, nowadays wired solutions are mainly used, because of high requirements with respect to robustness, security and low latency. Industrial protocols (i.e. Profinet) assign regular network access to the clients and ensure the transmission of data within a specific period and low latency. Yet industrial wireless is also attractive due to easy deployment and flexibility, and LC may be a preferred solution as explained below.
		2. LC based solutions may provide benefits over RF based solutions for industrial wireless with respect to,
			1. Suitable for dense deployment: Manufacturing belongs to the so-called dense wireless scenarios with multiple links maintained simultaneously all offering the above mentioned high service quality. LC can deliver safe wireless communications with low latency because it has well-confined propagation conditions in very small cells. Moreover, LC can be used complementary to RF systems for data off-loading.
			2. Coexistence with other RF services: One big issue for industrial wireless networks is coexistence with other services. Using other RF links in the same spectrum may result in unpredictable delays and contradicts low latency requirements. Getting dedicated spectrum for industrial wireless is one way. LC operates in unused spectrum and could be another way to alleviate the current situation. Note that ambient light impose little interference on LC as discussed below in “LC Technical Feasibility”.
			3. Robustness against jamming: it is possible for actors to easily jam the used RF spectrum from great distances outside the plant with simple RF devices. The use of RF-based wireless links instead of cables has obviously a potentially harmful impact on the safe operation of the connected manufacturing facilities in general. In addition, the presence of strong electromagnetic interference may not be suitable for RF communication like in a steel mill, in nuclear power plants or in a power station. On the other hand, LC is inert against RF jamming and EMI, the propagation is confined inside the plant. Jamming from a different light source outside the plant cannot penetrate opaque walls. LC receivers can suffer from interference from other LC sources. Therefore, LC receivers can be jammed using other LC transmitters that would provide a stronger interference signal relative to the desired signal. However, any jamming in LC can be easily detected and mitigated by selectively shielding the receiver from light coming from directions different from the desired source. The shielding could potentially be done by only using a hand..
	4. Healthcare
		1. Providing the same reliability and security as a wired connection with the flexibility of a wireless solution for indoor communications, including reliable and precise indoor positioning for patient/doctor/asset tracking as well as wireless connectivity in EMI sensitive environments like operating theaters or MRI rooms.

**LC Link Budget**

The entire methodology for the link budget calculations is presented in [30]. The link budget for a specific example deployment with specific components has been calculated to be between 30 – 40 dB when deployments at ranges of 2m – 4m in the referenced [30]. However, the LC systems have been demonstrated to operate at various distances from 0.1m to 200m.

**LC Metrics**

The strict definition of the LC metrics is left to the Study Group.

1. Data rate
2. SNR Link Margin Latency – average range
	1. PHY and MAC
3. Channel access fairness
4. Area capacity (area spectral density (bit/s/sqm))
5. Considerations for the MAC efficiency on the capacity – measured at the MAC SAP

**LC requirements**

The details of the following items should be addressed by the eventual LC Task Group in more detail during the standards development process.

1. Integration with and extension to 802.11 MAC
2. low-latency data delivery
3. Asymmetric device capability support (power, directivity, wavelength, sensitivity, backhaul network latency timings, etc.)
4. Peer to peer communications

**LC Technical Feasibility**

1. General Questions
	1. How does LC work?
		1. Any baseband electrical signal that is supplied to a light-emitting or laser diode (LED/LD) generates a light output with power proportional to the amplitude of the electrical signal. As a diode only works for positive current/voltage, the electrical signal needs to be positive only. Bipolar communication signals are typically realized around a positive bias (operating) point for which the LED/LD is active and has a linear input-output characteristic. The relationship between voltage and current is nonlinear, but the current-to-power relationship is rather linear, but only for positive drive currents. Note that temporary zero-crossing towards negative drive currents is inevitably clipped and cause severe waveform distortion. As a result, the information is typically encoded into a positive current of the electrical signal used to drive the LED/LD. The LED/LD effectively serves the purpose of an upconverter in RF that generates light-frequency waves with intensity proportional to the electrical current that flows through the device. The spectrum of the electromagnetic radiation is not noticeably correlated with the information signal[[1]](#footnote-1) and is dependent on the material/physical implementation of the LED/LD. For LEDs, this spectrum is typically very wide, while for LDs it is typically much narrower, yet still quite wider than the bandwidth of the baseband information signal itself. [1,2]
		2. Any light that is incident on a photodetector such as a photodiode leads to current flowing through the device, which is proportional to the light intensity. As a result, a photodiode converts light variations into current variations or a light information signal into a current information signal. The conversion from power to photocurrent is linear. The current information signal conveyed via the light from the transmitter to the receiver is then treated as any other electrical baseband information signal in a communication system. But it is real-valued and has non-negative amplitude. [1,2]
	2. How does LC work in a bright room with sunlight?
		1. The information signal is encoded in the light intensity variations. For high speed communication, these intensity variations are quite fast as the bandwidth of the information signal is in the order of tens to hundreds of MHz. Variations in sunlight and ambient light from light sources are quite constant relative to the light used for communication. As a result, they lead to zero or low-frequency signal interference that is easily avoided/filtered out. This is especially easy when an OFDM based communication protocol is used.
		2. A first possible distortion effect due to ambient light can occur when the ambient light is strong enough to saturate the receiver. This is very hard to achieve in practice for any reasonable communication scenario. Further issue caused by background light is additional shot noise (modelled as Gaussian noise) in the photodiode. Shot noise is related to the quantum nature of photons arriving randomly at the receiver over time. Usually, the corresponding fluctuation is much smaller than the signal, and the shot noise is only significant in bright sun or ambient light conditions. In typical short-distance scenarios, the shot noise is not strong enough to compromise the system performance. A typical light communication system can function even at high indirect sunlight illumination levels. [1,11]
	3. How does LC work when you turn off the lights?
		1. Visible light communication would typically no longer work, when you turn off the lights, i.e., there is no power transmitted in the visible light spectrum. In certain scenarios, one could resort to very low light illumination (lights are dimmed down to the point when they appear to be completely off) using extremely sensitive light detectors such as photomultipliers or avalanche photodiodes (APDs). However, for typical visible light communication systems that are currently being envisioned, communication would not be possible when the lights are off. In such a scenario, one would resort to infrared light for communication and/or radio frequency communication. [1,4,8,12]
	4. Can we see LC lights flicker?
		1. The human eye cannot really discern light changes above 10 kHz. Because communication lights change intensity (flicker) at rates in the order of 10s or 100s of MHz, no visible flickering effects should occur in a VLC system. [3]
	5. Is the flicker created by modulation safe?
		1. No extensive studies have been done on this effect. However, one would assume that it is no more harmful than is the flickering of a TV screen, computer screen or a mobile phone screen with a refresh rate of 30/60/120 Hz/240 Hz. [3] [33]
	6. Is LC a line of sight technology?
		1. By design, light communication can be made line-of-sight or non-line-of-sight technology. It all depends on the communication scenario (received power, light propagation) and the technology that is employed. [1,4,5]

Figure 1 An example of LoS and NLoS scenarios for LC operation

Transmitter

Detector

NLoS Scenario

Transmitter

Detector

LoS Scenario

* 1. If LC is a non-line-of-sight technology then how is it more secure than other wireless technologies?
		1. Light radiation (especially visible light radiation) is significantly easier to constrain and police compared to RF radiation. In addition, the extremely short light wavelengths lead to significant attenuation effects even over moderate distances. This leads to more confined operating environments where secrecy rates become relevant. [6,7] In addition, jamming light communication signals is harder to achieve than with RF solutions.
	2. Will LC work in my pocket?
		1. No, it is expected that when a LC enabled device is placed in one’s pocket, the communication protocol that is used will rely on RF communication. Light communication is envisioned as a technology adjunct to RF communication for devices that have multi-radio capabilities. [8]
	3. Can we enable LC to simultaneous uplink/downlink communications in 802.11?
		1. Yes, it could theoretically be achieved. Simultaneous uplink/downlink communications in LC can be achieved using the same or different wavelengths (colors) for the uplink and downlink, i.e. wavelength division duplex (WDD). The uplink could use infrared radiation at a certain wavelength, whereas the downlink could use visible light or infrared radiation depending on the illumination scenario. [9] However, as in frequency division duplex (FDD) in RF, WDD is a matter of cost, in particular in small user devices. Excellent RF isolation is obviously needed between transmitter and receiver in the same device.
	4. Are LC systems subject to multipath fading?
		1. Light communication systems typically employ incoherent modulation and demodulation. The light photons themselves interact constructively and destructively between each other. As there is no correlation between the individual light modes, the light that reaches a given surface on average is the same. At the same time, a typical photodiode detector has an area (in the order of mm) that is much larger than the size of an individual photon (in the order of hundreds of nm to a few um). Hence, receiver diversity over thousands of transmission wave modes is achieved in a photodetector, which mitigate some fading effects [1,10]. This should not be confused with multipath interference and inter-symbol interference, which still exist.
	5. What modulation techniques are available in the literature for LC?
		1. There have been many modulation techniques for light communication studied in the literature. A good overview of most modulation schemes is presented in [14] and illustrated here in Figure 2. This paper also has plenty of references to other papers on the topic of modulation scheme comparison.



Figure 2: Possible modulation formats for LC [14].

* + 1. About 30 different modulation schemes are presented in [14]. They can basically be categorized into two groups: single carrier modulation (SCM) such as on-off keying (OOK), pulse-position modulation (PPM), discrete Fourier transformation spread OFDM (DFT-S-OFDM), and multi carrier modulation (MCM), such as orthogonal frequency division multiplexing (OFDM). Below, two modulation schemes, each of which represents one group, are introduced for illustration.

***Use of OFDM for baseband modulation and the need for mitigation of multipath***

* + - 1. ***Implementation and typical symbol length:*** Implementation is almost equivalent to the implementation for RF communication with the additional constraint required to generate a real signal. The symbol lengths with FFT between 64 and 512 that are already present in the different 802.11 flavours work quite well for light communication as well. The guard intervals depend on the channel conditions, but for most channels (especially LoS) a very short cyclic prefix is required, as an example. We believe that the capabilities that are already available in 802.11 are suitable to the needs of light communication.

****

Figure 3: Example of an OFDM modulation and demodulation chain for LC.

***Use of DFT-s-OFDM for baseband modulation***

DFT-spread OFDM is one of the single carrier modulation schemes for LC that have lower PAPR property than most of MCM schemes such as OFDM. In LC, a signal with high PAPR can be distorted by not only a nonlinear power amplifier, but also a large DC bias which can seriously degrade system power efficiency. One of the advantages of DFT-s-OFDM comparing to other SCM schemes is that the orthogonal multiple access in frequency domain can be easily achieved. In LTE, it is called Single Carrier Frequency Domain Multiple Access (SC-FDMA). Figure 4 depicts an example of a DFT-s-OFDM modulation and demodulation chain for LC.



Figure 4 Example of a DFT-s-OFDM modulation and demodulation chain for LC

* 1. How does the backhaul work?
		1. The backhaul in light communication systems is expected to work as the backhaul for any wireless access network. The information signal at the two ends of the backhaul network (transmitting and receiving) is equivalent for an RF and for a light communication system. In terms of networking, the light communication systems are expected to provide much denser deployment of access points, which would lead to better frequency reuse from the point of view of the wireless access network, however, it would lead to denser and potentially more complicated backhaul networks. The tendency in wireless communications, however, has always been towards smaller and more densely deployed cells. Light communication is a natural extension of the existing communication paradigm stemming from this tendency. As an example, power over Ethernet (PoE) could be used to provide both data and power to the LED lighting. This has been done very effectively in the Edge Building in Amsterdam where over 6500 LED lights have been connected using PoE to provide saving in both installation costs and time [13]. For retrofitting of light communications into building environments where modern communication infrastructure does not exist, however, power line communication (PLC) could also be used. [9]
	2. How does uplink of LC-systems work?
		1. Light communication can also be used for uplink. Yet for certain use cases, a LC based uplink can be challenging due to potential energy limitations of mobile devices and potential glare from the produced light. For these use cases, the uplink could use infrared radiation. For devices that have RF capabilities, it is envisioned that RF communication may be used for uplink (hybrid LC/RF), as well as in parallel to light communication for “carrier aggregation” for both up- and downlink (aggregated LC/RF) [17].
	3. Can network connectivity be maintained under mobility scenarios?
		1. It is envisioned that LC systems are mainly used for indoor low mobility use cases. The network connectivity can be easily maintained within the coverage of a LC-light by adapting the data rate to the channel conditions. Still, the coverage of a LC-transmitter can be limited. When a user moves among neighboring LC-lights, fast handoff may be beneficial to reduce interruption time. For devices with RF capabilities, RF may be used as a fallback solution to maintain the connection during mobility.
	4. Does LC interfere with existing products that use the light medium, e.g., remote controls for TV sets?
		1. No, because the lower part of the base-band bandwidth, e.g., less than 100 kHz, can be easily removed such that it is not subject to any interference from slow varying signals and does not cause interference to other slow varying light signals.
	5. Does LC impact the color quality of lighting?
		1. No. Work in [3] shows that, for a DC-balanced modulating signal, with a non-varying average value, any fluctuations in the instantaneous driving current due to data modulation do not have any significant impact on the measured light quality metrics.
	6. Power consumption
		1. LEDs are being used for illumination and communications, removing constraints on the transmit power for the downlink.
		2. Using LC for uplink can be more power consuming. However, as discussed above in “how does uplink of LC-systems work”, when power consumption is an issue, the uplink could use infrared radiation or RF for uplink with similar level of power consumption as current 802.11 devices.
1. System Architecture
	1. LC may be able to use the basic service set (BSS), extended service set (ESS) and independent basic service set (IBSS). It is envisioned that infrastructure BSS such as shown in Figure 5 can be the most straightforward deployment. Here a LED-light serves as an AP with several stations associated to it. The coverage of one LED-light is usually limited in several square meters which can be easily calculated as the transmitter can be modelled as a Lambertian emitter [30]. Therefore neighboring BSSs may be interconnected by a distribution system (DS) to form an ESS in order to cover a large area. Interference may be experienced in the overlapped areas and coordination among neighboring BSSs can be helpful. Such architecture is especially suitable for enterprise use cases where multiple LED-lights coexist in the same room. IBSS, where stations communicate with one another directly in an ad-hoc manner, may also be useful. For example, an LED flashlight on a mobile device can be used as the transmitting device to directly communicate with another mobile device [29].
	2. In addition, Figure 6 shows a general system level architecture for a LC deployment. The visible light spectrum can be used to provide both illumination and communications, while the infrared spectrum can be used from mobile devices to provide the uplink.



Figure 5: Example of the overall architecture for LC.



Figure 6: Example of the overall architecture for LC.

1. Form of standardization
	1. The decision of whether LC should be a standalone standard (i.e., 802.11.3) or an amendment (802.11xx), should be left to the Study Group and 802.11 WG. However, the benefits of inheriting the upper portion of the 802.11 MAC and services it provides are seen as key enablers for the commercial success of the technology and therefore the LC TIG recommends that LC should be considered to become an 802.11 amendment rather than a standalone standard.
2. Reuse of 802.11 MAC
	1. The LC protocol is expected to reuse the existing facilities within 802.11, such as distributed coordination function (DCF), power save modes, session establishment / tear down procedure and block acknowledgement etc. However, modifications specific for the operation of LC may be suggested that could improve the efficiency for particular implementations.
	2. Assumptions that are potentially not valid in the LC context

STA may not necessarily see interference from neighboring STAs as shown in Fig. 4. However, this is a system design consideration and not a fundamental limitation.

1. Compatibility with other 802 wireless protocols
	1. Considering the LC TIG recommendation that the LC becomes an amendment to 802.11, then the LC TIG sees that the new amendment would be compatible with the relevant 802 protocols.
	2. The LC TIG would envision coexistence and hand-over between different 802.11 PHY types. There should be no coexistence issues with respect to the physical medium. However, potential channel aggregation with other available RF resources could lead to increased capacity.
	3. There are no known 802.11 devices that operate on the light medium, therefore coexistence is not an issue.
2. Difference with on-going 802 light communication standards (e.g., 802.15.7m/802.15.13) and ITU-T G.vlc
	1. The different MAC and PHY models between the IEEE 802.11 and the ITU-T recommendations effectively create two entirely different standards.
	2. The difference between LC and the existing 802 light communications standards is the use of the 802.11 MAC and associated services that are focused on local wireless area networks relative to the existing (802.15.7m and 802.15.13) efforts that are focusing on deploying the technology for wireless specialty networks. In addition, the coexistence and hand-over with other 802.11 PHY types creates a unique market capability for LC as part of 802.11. Similar to the differences between the 60 GHz work done within 802.15 and within 802.11, the use of the light spectrum with 802.11 technologies can uniquely address existing use-cases potentially covered by 802.15.13 as well as novel use-cases. The decision on the technical specifications of any 802.11 PHY would be determined by the eventual LC TG.
3. Demonstrated Systems
	1. There are numerous wireless LC systems demonstrated delivering data rates from 1 Mbps through to multiple Gbps [21-28]. However, these systems are generally based on proprietary technologies and there is a growing need to standardize the technology.

**LC Economic Feasibility**

A general presentation about the economic feasibility of LC is shown in [18].

1. Penetration of LED lighting
	1. LED lighting in 2017 still accounts for <10% of the over 45 billion lighting sockets available. Yet, LED lighting accounts for over 50% of the revenue for the lighting industry in 2017 and are fast replacing traditional light sources. It is anticipated that LED will replace over 50% of the current incandescent and florescent lighting by 2020 [18]



Figure 7 Global lamp installed base. Source: Philip Smallwood, co-chair of Strategies in Light and director of research at Strategies Unlimited presenting at the The LED Show conference, March 1 – 3, 2016

1. Balanced costs
	1. The infrastructure costs are expected to be similar to the installation of traditional lighting or Ethernet based networks. In other words, very reasonable in terms of the delivered functionality.
2. Known cost factors
	1. LC technology is well characterized in terms of cost and is tended for devices, such as fixed assets and mobile devices, which are also well known and characterized in terms of cost. The addition of a LC chipset that is based substantially on existing 802.11 technology in LED lights creates a very good estimate for the infrastructure costs. Similarly, the presence of optical modules and communications modules in mobile devices allows for a very good estimate of the expected/potential impact on device costs.
3. Consideration of installation costs
	1. These are substantially similar to current installations for lighting and the market forces are driving demand independent of LC, in particular for Power over Ethernet solutions suitable for smart buildings.
4. Consideration of operation costs
	1. The added energy cost to support LC is minimal since the energy that is used for illumination may also be used to provide wireless communications.
5. Market size/opportunity
	1. A 802.11 LC standard could be ready for 2021 with a likely global market of over USD 10 Billion. [31]
	2. LC offers significant market growth potential with over 550 million LED lights sold annually globally and 13% CAGR [18]

**LC Regulatory perspective (spectrum and health)**

The LC technology uses unregulated spectrum of visible light that does not need licensing. It has to be ensured, however, that LC systems do not present any health hazards (related to light intensity, color, or flicker) and that they are properly installed so as not to create any electromagnetic interference. [19] [20]

Adherence to the relevant local health and safety regulations regarding human eye safety and sensitivity is essential. Devices using LC should adhere to any local regulations regarding spurious RF emissions and should avoid causing interference in other RF spectrum bands.

**Recommendations**

The exploration done by the LC TIG shows the technical feasibility of building LC systems and indeed several demonstration systems have already been developed and are available on the market. However, these systems are generally proprietary with no interoperability. The identified market demand for the technology presents a good opportunity that could be exploited by a standardized technology.

Potential standardization of LC within IEEE802.11 would be unique relative to the existing IEEE 802 wireless light communications standardization efforts in that it would be targeted to enable more mass-market solution that could address significantly broader market segments relative to the standards developed in the 802.15 wireless specialty networks.

Therefore it is recommended by the LC TIG that,

* ***Considering the technical feasibility and identified market potential, the IEEE 802.11 WG starts a Study Group to better explore the scope of a potential standard.***

**References**

[1] J. M. Kahn and J. R. Barry, “Wireless Infrared Communications”, IEEE Proceedings, vol. 85, issue 2, February 1997.

[2] R. Mesleh, H. Elgala and H. Haas, “Performance Analysis of Indoor OFDM Optical Wireless Communication Systems”, IEEE Wireless Communications and Networking Conference (WCNC) 2012, 1 – 4 April, 2012.

[3] W. O. Popoola, “On Visible Light Communication and Quality of Light Emitted from Illumination LEDs”, IEEE Photonics Society Summer Topical Meeting Series 2016, 11 – 13 July 2016.

[4] O. Almer et al., “A SPAD-Based Visible Light Communications Receiver Employing Higher Order Modulation”, IEEE Global Communications Conference (GLOBECOM) 2015, 6 – 10 December 2015.

[5] J. Kosman et al., “60 Mb/s, 2 Meters Visible Light Communications in 1 klx ambient Using an Unlensed CMOS SPAD Receiver”, IEEE Photonics Society Summer Topical Meeting Series 2016, 11 – 13 July 2016.

[6] C. Rohner et al., “Security in Visible Light Communication: Novel Challenges and Opportunities”, Sensors & Transducers, vol. 192, issue 9, September 2015, pp. 9 – 15.

[7] A. Mostafa and L. Lampe, “Physical-layer Security for Indoor Visible Light Communications”, IEEE International Conference on Communications (ICC) 2014, 10 – 14 June 2014.

[8] S. Shao et al., “An Indoor Hybrid WiFi-VLC Internet Access System”, IEEE International Conference on Mobile Ad Hoc and Sensor Systems (MASS) 2014, 28 – 30 October 2014.

[9] H. Burchardt et al., “VLC: Beyond Point-to-Point Communication”, IEEE Communications Magazine, vol. 52, issue 7, July 2014, pp. 98 – 105.

[10] J. B. Carruthers, J. M. Kahn, “Modeling of Nondirected Wireless Infrared Channels,” IEEE Transactions on Communications, vol. 45, issue 10, October 1997, pp. 1260 – 1268.

[11] M. Beshr, I. Andonovic and M. H. Aly, “The Impact of Sunlight on the Performance of Visible Light Communication Systems over the Year”, SPIE Proceedings, September 2012.

[12] T. Borogovac et al., “Lights-off Visible Light Communications”, IEEE Global Communications Conference (GLOBECOM) 2015, 5 – 9 December 2011.

[13] Philips Lighting - <http://www.philips.com/a-w/about/news/archive/standard/news/press/2015/20150625-Philips-shines-light-on-opening-of-the-office-of-the-future-the-Edge-in-Amsterdam.html>

[14] M. Sufyian and H. Haas, “Modulation Techniques for Li-Fi”, ZTE Communications, April 2016, vol. 14 No. 2. Available at:

<http://wwwen.zte.com.cn/endata/magazine/ztecommunications/2016/2/articles/201605/t20160512_458048.html>

[15] V. Jungnickel, V. Pohl, S. Nonnig and C. von Helmolt, "A physical model of the wireless infrared communication channel," in IEEE Journal on Selected Areas in Communications, vol. 20, no. 3, pp. 631-640, Apr 2002.

[16] https://en.wikipedia.org/wiki/Stimulated\_emission

[17] M. Ayyash et al., "Coexistence of WiFi and LiFi toward 5G: concepts, opportunities, and challenges," in IEEE Communications Magazine, vol. 54, no. 2, pp. 64-71, February 2016.

[18] <https://mentor.ieee.org/802.11/dcn/17/11-17-0803-01-00lc-economic-considerations-for-lc.ppt>

[19] <https://mentor.ieee.org/802.11/dcn/17/11-17-0592-00-00lc-lc-tig-draft-report-ofcom-contribution.docx>

[20] Infocomm media development authority, <https://www.imda.gov.sg/regulations-licensing-and-consultations/frameworks-and-policies/spectrum-management-and-coordination/spectrum-planning/li-fi-technology>

[21] Sihua Shao ; Abdallah Khreishah ; Michael B. Rahaim ; Hany Elgala ; Moussa Ayyash ; Thomas D.C. Little ; Jie Wu, “An Indoor Hybrid WiFi-VLC Internet Access System”, IEEE 11th International Conference on Mobile Ad Hoc and Sensor Systems, 2014

[22] PureLIFI - <http://purelifi.com/lifi-products/>

[23] HHI - <https://www.hhi.fraunhofer.de/en/departments/pn/research-groups/metro-access-and-in-house-systems/research-topics/optical-wireless-communications/optical-wireless-communication.html>

[24] IPMS - <http://www.ipms.fraunhofer.de/de/research-development/wireless-microsystems.html>

[25] VLNCOMM - <http://www.vlncomm.com/vlc-technology/products/>

[26] FireFly - <http://www.fireflywirelessnetworks.com/home.html>

[27] OLEDCOMM - <http://www.oledcom.com/>

[28] Mengjie Zhang, Meng Shi, Fumin Wang, Jiaqi Zhao, Yingjun Zhou, Zhixin Wang, Nan Chi, “4.05-Gb/s RGB LED-based VLC System Utilizing PS-Manchester Coded Nyquist PAM-8 Modulation and Hybrid Time-frequency Domain Equalization”, Optical Fiber Communication Conference, 2017

[29] Giorgio Corbellini, Kaan Aksit, Stefan Schmid, Stefan Mangold, and Thomas R. Gross, “Connecting Networks of Toys and Smartphones with Visible Light Communication”, IEEE Communications Magazine, vol. 52, issue 7, July 2014, pp. 72 – 78.

[30] Dobroslav Tsonev, Nikola Serafimovski, Murat Uysal, Tuncer Baykas, Volker Jungnickel, "IEEE 802.11-17/0479r0 Light Communications (LC) for 802.11: Link Margin Calculations", IEEE 802 Plenary Session, Vancouver, March 2017

[31] <https://www.gminsights.com/pressrelease/LiFi-market>

[32] <http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html>

[33] https://www.pcmag.com/article2/0,2817,2379206,00.asp

1. LEDs have by nature of their spontaneous emission a spectral width typically covers 10s of nanometres in the optical domain. For LDs having single mode characteristics, spectral width can be much lower, due to stimulated emission [16]. [↑](#footnote-ref-1)