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Visible Light Communication – The Journey So Far

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Abstract: An unprecedented demand for connecting physical objects with the internet expedites the realization of internet of things, thus creating new challenges to explore new spectrums which are suitable for communication. Visible light communication (VLC) is one promising candidate not only to remove the spectrum crunch issues but also to offer virtually unlimited, unregulated spectrum. This paper discusses how VLC can help solving spectrum crunch, non-availability issues of radio frequency spectrum and how readily available spectrum of VLC can be utilized to cope up with the bandwidth requirements of next-generation networks. Furthermore, this paper also lists the technological innovations in the area of VLC from early days till present and its possible applications in various domains.

Keywords: visible light communication (VLC), spectrum crunch, internet of things (IOT), eco-friendly technology

1 Introduction

Have you ever wondered why we are asked to turn off our mobile phones during aircraft take-off and landing? Why are we asked not to use mobile phones in intensive care units (ICUs) of health care facilities and inside intrinsically safe environments like petrochemical industry? Why do coal miners and sea divers not use radio frequency (RF) communication while performing their duties? Why is global positioning system (GPS) unavailable/inaccurate in an indoor environment for navigation?

What if we can use our mobile phones (voice and data) in ICUs, during take-off and landing, at intrinsic safe environments and stay connected with the online world? What if we can eliminate/minimize the detrimental effects of RF radiations and make the communication utterly safe for living tissues? What if coal miners and sea divers have sophisticated mode of communication inside mines and sea which can possibly make their minatory job safer? What if we can have precise indoor positioning system when GPS signals are weak/lost bringing convenience to our lives? What if we can reduce the RF spectrum congestion without compromising on the quality of service? What if the light emitting diode (LED) installed on a water kettle can pass the information to the user when water is hot enough to be used for coffee, thus economizing electricity? What if cars head/back lights and street lights can communicate amongst each other, sharing necessary information regarding inconvenient situations, emergencies and help avoiding traffic congestion/road accidents? What if lighting becomes energy efficient? What if jewellery and wearables can communicate our health status to the concerned person enabling continuous monitoring of physical and physiological parameters of an individual for assessment and management?

Fortunately, all the aforementioned questions have reply in the affirmative and one possible solution is visible light communication (VLC). VLC is a sub-class of optical wireless communication in which the electromagnetic (EM) spectrum ranging from 380 nm to 780 nm is utilized. This is basically the region in EM spectrum which we can see through our naked eye, i. e. visible light. In this type of communication, LED(s) is(are) used as a transmitter and photodiode(s) or camera(s) is(are) used as a receiver. Data are transmitted by switching on and off the LEDs at a higher rate than what human eye can discern. Furthermore, LEDs are 60 to 80 % more energy efficient than the conventional incandescent and fluorescent lamps. Apart from energy efficiency, LEDs are more reliable (in terms of mean time before failure) and environmental friendly (mercury free). But how can VLC resolve all the aforesaid issues?

Offering in-flight data access to passengers by plane manufacturers is an active area of research, but the challenges associated to this service are EM interference (EMI) with communication and navigation system of an aircraft, compatibility issues with the flight equipment and the offered baud rate per user. However, a passenger reading lamp gives a decent coverage area which can be used as a transmitter, transmitting high stream of data and for reception, and a passenger data adaptor consisting of photodiode and infrared LED can be installed which can act as a receiver. EMI has an adverse

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effect on medical devices used in critical care setup; however, ceiling lights in ICUs are always switched on for good reasons and do not have antagonistic effect on medical equipment or patient health. In intrinsically safe environments like underground mines, terrestrial RF communication models cannot be right away applied to underground mines due to higher attenuation levels and presence of inflammable gases like methane and hazardous environment in addition to the power restriction at the transceiver which ensures ignition is not caused either by sparking or by heating effects. Similarly, RF technologies are not very practical to be employed in underwater environment since seawater is salty and inductive which causes RF waves to attenuate radically. Acoustic systems for medium- to long-range communication have issues of extremely low data rate and high latency. On the other hand, VLC can offer better penetration of light waves in water, higher data rates (in tens of Mbps) and lower latency than their counterparts. GPS fails to work in an indoor environments mainly because of signal attenuation, poor satellite coverage, multi-path effect and EMI but if we look around, in a typical indoor environment, lights are placed in a regular manner and they can act as a beacon for indoor navigation. Furthermore, pre-installed lights (with little or no modification) can become a source for home automation. Modern vehicles are now equipped with LED front and back lights and street lights are also LEDs operated; thus an intelligent transportation network can be created in which vehicles can communicate with other vehicles and also with the street lights. All these solutions will be utilizing entirely different spectrum from RF so there will be no additional burden on expensive spectrum. Indeed, VLC is license free and has virtually unlimited spectrum which can help resolving RF spectrum congestion.

This paper mainly introduces the major milestones in the domain of VLC that have been achieved by various researchers around the globe which are discussed in Section 2. Section 3 outlines the misconceptions about VLC and Section 4 talks about how we can get benefit from VLC in our daily lives? The paper is concluded in Section 5.

2 Timeline for VLC

Humans are using light as a radix of communication since ages. . In fact, using light as a source of communication can be considered as a primordial tool for telecommunications. People use mirrors to reflect the sun light towards a particular direction to gain the attention of some other person. Light houses are being used since fifth-century BC as an aid to navigation for marinetime pilots. Tribal and indigenous people light the fire to invite people from the tribe for some gathering and the same technique is being used for acquiring emergency help. But, if we talk about modern ways of communication, indeed VLC is a very new concept. Modern VLC has a history for less than two decades. Table 1 gives a detailed description how VLC has evolved as a major contender for next-generation networks.

3 Misconceptions about VLC

While implementing VLC through an indoor lighting, a set of questions arise which need to be addressed and the questions are

(a) What happens to the communication link if the light is turned off (completely/partially)?
(b) Will it create an unpleasant effect on the eye if LED is blinked for data transmission?
(c) Is VLC a unidirectional communication technology?
(d) What about the interference from other light sources like sunlight, fluorescent and incandescent lamps and how to get rid of it?
(e) Do receiver needs to be in the line-of-sight (LOS) with the transmitter?
(f) Will VLC eliminate RF communication?

The answers to the above listed questions are:

(a) [16] defines the limits on the transmit power which are low enough to be considered as “off” state from user perspective. Results show that for both day- and night-time scenarios, data coverage can be maintained in “lights-off” mode while delivering data rates of several Mbps with low complexity devices. However, if the light is completely turned off then there will be no communication link.
(b) Human eye can detect few tens of frames/blinking per second, but in VLC, transmitter is made to blink at far higher speed which a human eye cannot perceive. For a 1 Gbps communication link using a single LED, the LED will be switched ON/OFF 1 billion times a second and for a naked human eye, it is impossible to detect the blinking.
(c) VLC can be used in a bi-directional configuration where VLC is used for downlink and typically IR is used for uplink in order to avoid visual inconvenience.

Table 1: Timeline for VLC.

Year	Country	Major milestone
1999	Hong Kong	Realized that LED can be used as a source of data communication and experimentation begins [1].
2001	Japan	Contributions from Keio University for broadband VLC using white LED [2]. Feasibility of two modulation schemes namely on–off keying (OOK) and orthogonal frequency division multiplexing (OFDM) were investigated and found to work well in plural white LEDs
2003	Japan	Formation of Visible Light Communication Consortium (VLCC) responsible for developing VLC standards [3].
2004	Japan	Fundamental analysis for visible light communication system using LED lights was a great contribution from Keio University in which mathematical modelling of VLC system was given with rigorous analysis [4].
2005	Japan	Land trials of VLC communications to transmit information to mobile phones, with throughput estimated at 10 kbps and several Mbps using fluorescent light and an LED [5].
	Japan	An architecture for high-speed parallel wireless VLC system using 2D image sensor and LED transmitter was proposed by Keio University which increased the data rate by 50 times [5].
	Global	Wireless World Research Forum (WWRF) initiation towards VLC [6].
2007	Japan	Demonstration of a LED-backlit liquid crystal display television while transmitting information to a personal digital assistant (PDA) via light; Fuji Television [5].
	United States	Global Recognition – Scientific America publishes paper on VLC, “Broadband Room Service by Light” [7].
	Japan	Visible Light Communications Consortium (VLCC) in Japan proposed two standards:Visible Light Communication System StandardVisible Light ID System StandardJEITA (Japan Electronics and Information Technology Industries Association) accepted these standards as JEITA CP-1221 and JEITA CP-1222 [8].
2008	US and EU	United States (US) and European Union (EU) funded research projects on VLC [9].
	EU	Development of global standards for home networks, including the use of optical wireless communication (OWC) employing IR and VLC technologies; European Union-funded OMEGA project [10].
	Japan/US	VLCC in Japan and the International Infrared Data Association (IrDA) working together on specification standards in the United States [5].
2009	Japan	100-Mbps full-duplex multi-access visible light communication system over a distance of 3 m utilizing optical carrier sense multiple access with collision avoidance (CSMA/CD) [11].
	Japan	VLCC issued their first specification standard which incorporates and expands upon core IrDA specification and defined spectrum to allow for the use of visible light wavelengths [5].
	Global	Call for contributions on IEEE 802.15.7 [12].
2010	Japan	Demonstration of VLC with the indoor GPS [13].
	Germany	Transmission of information at 500 Mbps over 5 m, Siemens and the Heinrich Hertz Institute [5].
	United Kingdom	A 1.25-Gb/s indoor cellular optical wireless communications demonstrator over 3-m distance with a bit error rate (BER) of 10^{-9} [14].
2011	Japan	Demonstration of applicability of VLC in intelligent transportation system by VLCC and Japan Traffic Management Technology Association [13].
	United Kingdom	Professor H. Haas Global TED talk “wireless data from every bulb.”
	Global	IEEE publishes IEEE 802.15.7 standard for short-range wireless communication technologies [12]. A PHY and a MAC layer for short-range OWCs using visible light in optically transparent media are defined.
	United Kingdom	Organic VLC by Northumbria University [15].
	United States	Concept of “Lights off Visible Light Communications” addresses a very important question what happens to VLC link when lights are off/dim [16].
	Global	International Organization for Standardization (ISO)/International Electro-technical Commission (IEC) 17,417 Standard [17].
2012	Taiwan	500Mbps WDM visible light communication systems over a distance of 10 m with a BER of 10^{-9} with the help of red and green laser pointer lasers [18].
	Spain	1-Gb/s line-of-sight (LOS) transmission over a phosphorescent white LED by using rate-adaptive discrete multi-tone modulation with a BER of 1.5×10^{-3} [19].
	Spain	3.4 Gbit/s visible optical wireless transmission based on RGB LED with a BER of 2×10^{-3} [20].
2013	Japan	Indoor navigation system for visually impaired people using visible light communication employing LED lights and a geomagnetic correction method of the geomagnetic sensor integrated in a smartphone [21].
	United Kingdom	A gigabit/s indoor wireless transmission using MIMO–OFDM visible light communications [22]. Experimental demonstration achieves 1 Gbps transmission link utilizing four transmitting channels each of 250 Mbps.
	Japan	JEITA CP-1223 standard [8].

(*continued*)

Table 1: (*continued*)

Year	Country	Major milestone
2014	United Kingdom	Design and implementation of secure and reliable communication using OWC [23].
	United Kingdom	Secure barcode-based visible light communication for smartphones [24].
	Japan	Formation of Visible Light Communications Association (VLCA) [25].
2015	United States	Indoor positioning in high-speed OFDM visible light communications [26].
	Hong Kong	Wearables can afford: Light-weight indoor positioning with visible light [27].
	Hong Kong	4.5-Gb/s RGB-LED-based WDM visible light communication system employing CAP modulation and RLS-based adaptive equalization having system BER of 3.8×10^{-3} [28].
2016–2017	United States	MIT Technology Review/OpenMind features Li-Fi, the New Frontier in Communications [29].
	Hong Kong/ Taiwan	Visible Light Communication Using Receivers of Camera Image Sensor and Solar Cell [30].
	United Kingdom	Towards 10 Gb/s orthogonal frequency division multiplexing-based visible light communication using a GaN violet micro-LED [31].
	United States	Gigabit-per-second white light-based visible light communication using near-ultraviolet laser diode and red-, green-, and blue-emitting phosphors [32]

Another advantage of using different frequencies for uplink and downlink is interference avoidance.

(d) Light falling from other sources can be easily cancelled out at the receiver as the spectrum of electrical noise due to ambient light is mostly concentrated at very low frequency (<20 Hz). In order to cancel out the effect of noise, a minimum voltage detection circuit consisting of differential amplifiers and adaptive minimum voltage detector can be used to cancel the minimum offset voltage of the received signal. Furthermore, techniques like low-pass filtering, band-pass detection and adaptive threshold detection can be used to eliminate the effect of interference from ambient light sources.

(e) For VLC, both LOS and NLOS exist. A high-speed, 200 Mbps NLOS link has been demonstrated in [33]. The linked achieved a BER less than 2×10^{-3}in the presence of background noise from phosphorus-based LEDs.

(f) Future-generation networks will be employing heterogeneous schemes and VLC has appeared as a complementary technology to overcome spectrum crunch issues. A hybrid VLC and RF network was proposed [Ref] in order to ease spectrum congestion issue where downlink was done through VLC and uplink was done through RF-based Wi-Fi. Experimental results reveal that the proposed hybrid Wi-Fi-VLC internet access system outperforms conventional Wi-Fi in terms of throughput in crowded environments. So VLC will be working in conjunction with RF technologies in future heterogeneous networks.

4 Applications of Visible Light Communication and Commercialization

The next-generation networks will not be based on a single-access technology; somehow, these systems will incorporate a number of different complementary access technologies. The paradigm shift from internet of people to internet of thing (IoT), industrial internet of thing, and internet of everything has increased the need and applications of VLC many folds and VLC can act as a catalyst to speed up this revolution.

VLC has its application in intelligent transportation system, home automation, underwater communication networks, safe communication at RF hazardous (petrochemical industries, mining) and precarious (hospitals, aircraft) places, health monitoring, indoor navigation, navigation for visually impaired people, location-based services, LED-based shopping windows, inventory management, asset tracking, intelligent museums, targeted advertisement and communication, entertainment, high-speed data communication, near-field communication and energy-efficient lighting. Apart from these applications, VLC has its applications in defence industry as well because light cannot pass through the concrete structure (unlike RF waves), therefore, giving inbuilt security against eavesdropping [34]. We can summarize the applications of VLC into five categories based on their as shown in Figure 1.

Up till now, we have defined the applications of VLC in a generic fashion, for completeness, we discuss a VLC

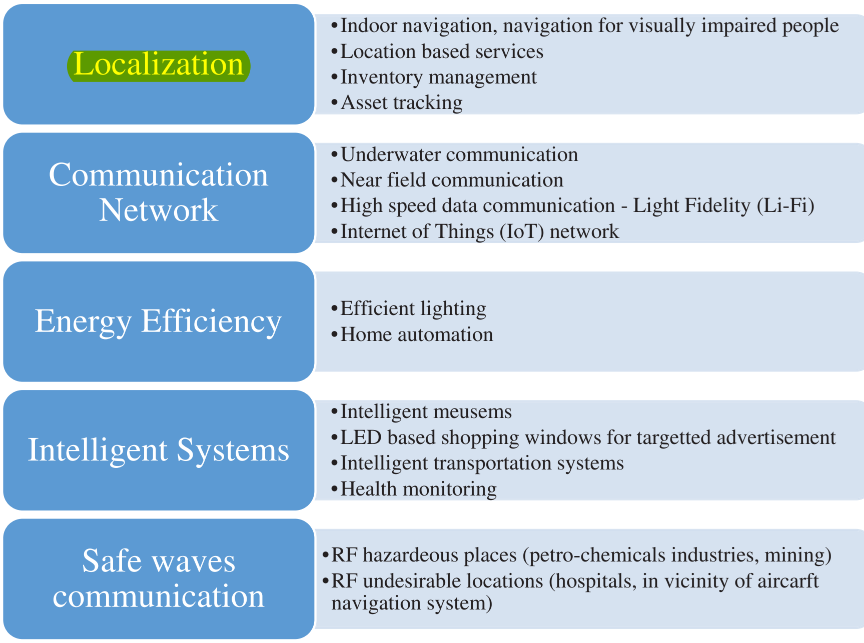

Figure 1: Applications of visible light communication.

network employing IoT in detail. VLC not only has the potential to solve spectrum crunch issues but also helps connecting billions of IoT devices, thus bringing revolution to human life. For instance, mornings can be made smarter by integrating VLC with IoT. An LED-enabled fitness band (a wearable device) can gracefully awake a person and pass the information of the user to other connected devices via VLC link which can result in a series of actions. Photodiodes attached to the table lamp can be asked to increase the light intensity, intelligent thermostat after receiving information from fitness band can be asked to bring the washroom temperature level in comfort zone and an LED- and photodiode-enabled electric kettle can be switched on. Similarly, curtains can go higher, home ventilation system can start, bathtubs can be filled, weather report and latest news can be displayed, surveillance system report can be shared, cars can automatically start and security gates can be opened and closed. These chains of events are not initiated by the user but the sensors/actuators connect with user/machines and make the decision by learning user life cycle patterns, thus giving rise to a sustainable energy-efficient communication network.

The transmitters for VLC (LEDs) are getting smarter and are penetrating the market at an exponential rate. The projected LED lighting market will be more than US $ 63.1 billion by 2020 [35]. On the other hand, the forecasted global mobile data traffic will be 88.7 EB per month by the end of 2016. Global IP traffic will increase nearly threefold over the next 5 years [36]. This is mainly because of two reasons, i.e. the high utilization of bandwidth-hungry applications and swift increase in the number of users. In simple words, we are running out of spectrum and if we do not explore other parts of EM spectrum, it will be nearly impossible to handle future predicted data traffic. If numerous applications shift to VLC, RF spectrum congestion is expected to be alleviated, which is a dire need of the hour. Not everything about LEDs and VLC is good and there is also a dark side of LED. LEDs contain lead, arsenic, nickel and a dozen other potentially toxic substances. O[illegible]xposure to light can cause retinal injury, vision-related accidents, damage to the films used in X-rays and film photography. Although, there exist prototypes in literature [16], in which low intensity of light is used for communication, however, the data rates achieved utilizing extremely low intensity light are not suitable to bandwidth-hungry applications. When the light is completely turned off, then there will be no communication. Last but not the least, slight modification is needed to enable VLC in the existing infrastructure, which will bring additional cost.

As far as commercialization of VLC is concerned, the researchers and scientists are actively working to develop ready to use devices supporting VLC. PureLiFi Ltd, has developed a LiFi-X Access Point and LiFi-X Station which supports power over ethernet, multiple access, handover for seamless switching between lights/access points with uplink and downlink data rate of 43 Mbps. Fraunhofer-Gesellschaft has developed a high-speed optical wireless local link with a peak data rate of 1 Gbps with the low latency of less than 2 msec using high-power LEDs. Disney Research has also developed various testbeds for VLC ranging from LED to LED software protocols to entertainment testbeds. Other than the above-mentioned companies, many big technology players like Apple, Byte Light, Casio, Intel, LVX system, Philips and Samsung are also playing their active role in order to bridge the gap between laboratory experimentations and product development for commercialization.

5 Conclusion

In this paper, the author has recapitulated the advancements in the area of VLC from early times till present day. One can discern from VLC timeline that it is not anymore a theoretical concept, but this technology is expeditiously heading towards maturity. With the evolution on IoT, the objective of future communication networks is not limited to connecting people with a high-speed link but the internetworking of physical devices, thus creating newfangled opportunities to develop contemporary networks. These networks will give rise to more bandwidth-hungry applications resulting in more bandwidth demand. VLC having virtually unlimited, licence-free band not only resolves the spectrum crunch concern but also offers adequate bandwidth to accommodate impending bandwidth requirements by the networks. The applications of VLC are extended in every way of life and the time is not far when a common man will be benefiting from environmental friendly, green and promising technology in his/her everyday life. We must realize that RF is only one part of the colossal EM spectrum and there exists a great potential in exploring other parts of EM spectrum which are well-suited for communication purposes.

The unique characteristics are that light is inherently safe and cannot penetrate through a concrete structure compartmentalize it as the only safe technology for communication in an intrinsically safe and efficacious secure environments. Future research and development will be in overall system optimization, development of more accurate outdoor channel models pandering to conditions of smog, fog, mist and dust, integration of VLC networks with the existing communication networks and development of low-cost optimized hardware for particular VLC applications. There is also a dire need of redesigning LEDs by the manufacturers minimizing the use of hazardous metals, thus making them a truly eco-friendly technology.

References

1. Pang G, Ho KL, Kwan T, Yang E. Visible light communication for audio systems. IEEE Trans Consum Electron. 1999;45 (4):1112–18.
2. Tanaka Y, Komine T, Haruyama S, Nakagawa M Indoor visible communication utilizing plural white LEDs as lighting. In: 12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2001, Vol. 2, IEEE, Sep 2001:F-81.
3. Visible Light Communication Consortium. Available at: http://www.vlcc.net/?ml_lang = en. Accessed: 16 Jun 2017.
4. Komine T, Nakagawa M. Fundamental analysis for visible-light communication system using LED lights. IEEE Trans Consum Electron. 2004;50(1):100–07.
5. Ghassemlooy Z, Popoola W, Rajbhandari S. Optical wireless communications: system and channel modelling with Matlab®. Boca Raton, FL: CRC Press, 2012.
6. Wireless World Research Forum. Available at: http://www.wwrf.ch/. Accessed: 19 Jun 2017.
7. Kavehrad M. Broadband room service by light. Sci Am. 2007;297(1):82–87.
8. JEITA Standards. Available at: http://www.jeita.or.jp/cgi-bin/standard_e/list.cgi?cateid = 1&subcateid = 50. Accessed: 17 Jun 2017.
9. Saadi M, Sittivangkul T, Zhao Y, Wuttisittikulkij L, Sangwongngam P, Dec. System demonstration for visible light communication using adaptive threshold detection for low data rate applications. In: 2012 IEEE International Conference on Electron Devices and Solid State Circuit (EDSSC), IEEE, 2012:1–3.
10. Visible Light Communication Omega Project. Available at: http://visiblelightcomm.com/tag/omega-project/. Accessed: 20 June.
11. Lin KIX, Hirohashi K High-speed full-duplex multiaccess system for LED-based wireless communications using visible light. In: Proc of the International Symposium on Optical Engineering and Photonic Technology (OEPT), Jul 2009:1–5.
12. IEEE Standard for Local and Metropolitan Area Networks–Part 15.7. Available at: https://standards.ieee.org/findstds/standard/802.15.7-2011.html. Accessed: 26 Jun 2017.
13. Haruyama S. Visible light communications: recent activities in Japan. Smart Spaces: A Smart Lighting ERC Industry—Academia Day at BU Photonics Center, Boston University, 8 Feb 2011:49 pages
14. Le Minh H, O'Brien D, Faulkner G, Bouchet O, Wolf M, Grobe L, et al. A 1.25-Gb/s indoor cellular optical wireless communications demonstrator. IEEE Photonics Technol Lett. 2010;22 (21):1598–600.
15. Optical Communicating Research Group. Available at: http://soe.northumbria.ac.uk/ocr/. Accessed: 27 Jun 2017.
16. Borogovac T, Rahaim MB, Tuganbayeva M, Little TD Lights-off" visible light communications. In: 2011 IEEE GLOBECOM Workshops (GC Wkshps), IEEE, Dec 2011:797–801.
17. International Organization for Standardization. Available at: http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber = 59692. Accessed: 5 Jul 2017.

18. Lin WY, Chen CY, Lu HH, Chang CH, Lin YP, Lin HC, et al. 10 m/500Mbps WDM visible light communication systems. Opt Express. 2012;20(9):9919–24.
19. Khalid AM, Cossu G, Corsini R, Choudhury P, Ciaramella E. 1-Gb/s transmission over a phosphorescent white LED by using rate-adaptive discrete multitone modulation. IEEE Photonics J. 2012;4(5):1465–73.
20. Cossu G, Khalid AM, Choudhury P, Corsini R, Ciaramella E. 3.4 Gbit/s visible optical wireless transmission based on RGB LED. Opt Express. 2012;20(26):B501–B506.
21. Nakajima M, Haruyama S. New indoor navigation system for visually impaired people using visible light communication. EURASIP J Wireless Commun Netw. 2013;2013(1):1–10.
22. Azhar AH, Tran TA, O'Brien D. A gigabit/s indoor wireless transmission using MIMO-OFDM visible-light communications. IEEE Photonics Technol Lett. 2013;25(2):171–74.
23. Saadi M, Bajpai A, Zhao Y, Sangwongngam P, Wuttisittikulkij L. Design and implementation of secure and reliable communication using optical wireless communication. Frequenz. 2014;68(11-12):501–09.
24. Zhang B, Ren K, Xing G, Fu X, Wang C. SBVLC: secure barcode-based visible light communication for smartphones. IEEE Trans Mobile Comput. 2016;15(2):432–46.
25. Visible Light Communication Association. Available at: http://vlca.net/about-vlca/. Accessed: 26 Jun 2017.
26. Aminikashani M, Gu W, Kavehrad M Indoor positioning in high speed OFDM visible light communications. *arXiv preprint arXiv:1505.01811*. 2015
27. Yang Z, Wang Z, Zhang J, Huang C, Zhang Q Wearables can afford: light-weight indoor positioning with visible light. In: Proceedings of the 13th Annual International Conference on Mobile Systems, Applications, and Services, ACM, May 2015:317–30.
28. Wang Y, Huang X, Tao L, Shi J, Chi N. 4.5-Gb/s RGB-LED based WDM visible light communication system employing CAP modulation and RLS based adaptive equalization. Opt Express. 2015;23(10):13626–33.
29. Li-Fi, the New Frontier in Communications. Available at: https://www.bbvaopenmind.com/en/li-fi-the-new-frontier-in-communications/. Accessed: 3 Jul 2017.
30. Liu Y, Chen HY, Liang K, Hsu CW, Chow CW, Yeh CH. Visible light communication using receivers of camera image sensor and solar cell. IEEE Photonics J. 2016;8(1):1–7.
31. Islim MS, Ferreira RX, He X, Xie E, Videv S, Viola S, et al. Towards 10 Gb/s orthogonal frequency division multiplexing-based visible light communication using a GaN violet micro-LED. Photonics Res. 5(2):A35–A43.
32. Lee C, Shen C, Cozzan C, Farrell RM, Speck JS, Nakamura S, et al. Gigabit-per-second white light-based visible light communication using near-ultraviolet laser diode and red-, green-, and blue-emitting phosphors. Opt Express. 2017;25(15):17480–87.
33. Cossu G, Khalid AM, Corsini R, Ciaramella E 2013. Non-directed line-of-sight visible light system providing high-speed and robustness to ambient light. In *Optical Fiber Communication Conference*. Optical Society of America.
34. Saadi M, Zhao Y, Naseer O, Wuttisittikulkij L. A beam scanning-based indoor localization system using light emitting diodes. Eng J. 2016;20(3):197–206.
35. Global LED Market Size, Regional Outlook, Application Analysis, Competitive Insights and Forecasts, 2014 – 2020 from Hexa Research. 2014.
36. The Zettabyte Era - Trends and Analysis, Cisco® Visual Networking Index (VNI) White paper. Document ID: 1465272001812119. Updated 2 Jun 2016