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Visible light communication: applications, architecture, standardization and research challenges☆

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ABSTRACT

The Radio Frequency (RF) communication suffers from interference and high latency issues. Along with this, RF communication requires a separate setup for transmission and reception of RF waves. Overcoming the above limitations, Visible Light Communication (VLC) is a preferred communication technique because of its high bandwidth and immunity to interference from electromagnetic sources. The revolution in the field of solid state lighting leads to the replacement of florescent lamps by Light Emitting Diodes (LEDs) which further motivates the usage of VLC. This paper presents a survey of the potential applications, architecture, modulation techniques, standardization and research challenges in VLC.

1. Introduction

The limited radio frequency spectrum puts constraints on the increasing demand for ubiquitous connectivity and high capacity. According to CISCO, there will be an 11-fold increase in mobile data traffic in 2018 compared to 2013 as shown in Fig. 1 [1]. The increase in the number of devices accessing the mobile networks is the primary reason for the drastic increase in mobile data traffic. Along with this, the development of online social services (such as Facebook and Twitter) has further increased the mobile data traffic. Apart from the spectrum deficiency issues in RF wireless communication, interference is another problem since most wireless devices are electromagnetic. The RF communication suffers from problems such as the following. (a) Interference, according to Federal Aviation Administration (FAA) the use of mobile phones on aircraft causes interference with communication and navigational systems. Along with this, mobile phones on aircraft will also cause disruption with ground system towers as argued by the Federal Communication Commission (FCC). (b) Regardless of the interference, it is clear that in a wireless communication system that needs very low latency requirements (such as in vehicular communication, safety system), the use of radio frequency is not suitable due to its bandwidth limitations. (c) As RF waves easily penetrate the walls, they suffer from security issues. (d) The increase in RF waves, transmission power beyond a certain limit results in risks to human health. (e) RF communication suffers from power inefficiency, because we require a separate setup for communication of the RF waves. To overcome the drawbacks of the RF communication systems, it is imperative to design new communication technologies.

Visible Light Communication (VLC) systems employ visible light for communication that occupy the spectrum from 380 nm to 750 nm corresponding to a frequency spectrum of 430 THz to 790 THz as shown in Fig. 2. The low bandwidth problem in RF communication is resolved in VLC because of the availability of the large bandwidth as illustrated in Fig. 2. The VLC receiver only receives signals if they reside in the same room as the transmitter, therefore the receivers outside the room of the VLC source will not be able to receive the signals and thus, it has the immunity to security issues that occurs in the RF communication systems. As a visible light source can be used both for illumination and communication, therefore, it saves the extra power that is required in RF communication. Keeping in view the above advantages, VLC is one of the promising candidates because of its features of non-licensed channels, high bandwidth and low power consumption.

Potential applications of VLC include Li-Fi, vehicle to vehicle communication, robots in hospitals, underwater communication and information displayed on sign boards. The Li-Fi uses visible light for communication to provide high speed internet up to 10Gbits/s. VLC can be used in vehicular communication for lane change warning, pre-crash sensing and traffic signal violation warning to avoid accidents. These applications require communication with low latency which is provided by VLC because of its high bandwidth and easier installation due to the existing presence of vehicle lights and traffic signals. VLC

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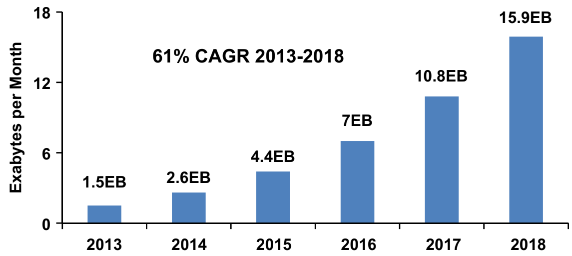


Fig. 1. Global mobile data traffic [1].

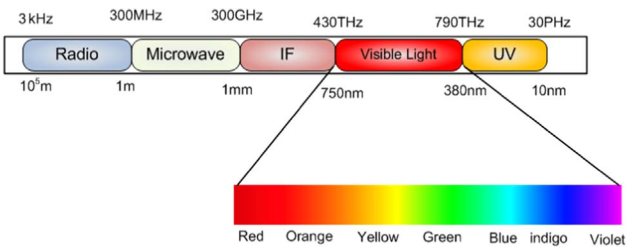


Fig. 2. VLC frequency spectrum.

also has applications in areas that are sensitive to electromagnetic waves, such as aircrafts and hospitals where the radio signals interfere with the waves of other machines. Visible light is used to provide both lighting and information using VLC techniques. For example, we use lighting in the room to provide the room number identification and other information about the building.

The challenges that exist in the implementation of VLC include (a) interference with the ambient light sources, (b) interference between VLC devices, and (c) integration of the VLC with existing technologies, such as Wi-Fi. To cope with the above challenges, a standardization of VLC is necessary. Four standards are developed that include Japan Electronics and Information Technology Industries Association (JEITA) CP-1221, JEITA Cp-1222, JEITA Cp-1223 and IEEE 802.15.7. In 802.15.7, only MAC and PHY layer are defined for short range communication using visible light. On the transmitter side, white light is generated based on wavelength converters and LEDs. White light based on LEDS is generated in dichromatic, trichromatic and tetra chromatic modes. The data on the transmitter side is modulated by modulating the light, however, the modulation should be done in a way to avoid flickering. Also, the dimming level that is selected for the modulation should be such that it is supported by the illuminating LEDs. The typical VLC receiver consists of an amplification circuit, optical filter and optical concentrator.

In this paper, a survey of applications, architectures, standards and research challenges is presented due to the potential of the VLC to be used for communication in the future. The rest of the paper is organized as follows: Section 2 introduces a brief history of VLC. Section 3 introduces the potential applications of VLC, Section 4 describes the architecture of VLC systems. In Section 5, the standardization of VLC is discussed and Section 6 is aimed to describe the modulation techniques for VLC. Section 7 introduces the open research issues. Finally, a summary of the paper is presented in Section 8.

2. Brief history

In ancient times, light was used to convey messages using methods such as fire and smoke signals. The Roman used polished metallic plates for sunlight reflection to carry out long distance signaling. Semaphore lines based Optical Communication (OC) systems were developed in the 1790 s. The first visual telegraphy system was developed by the Claude Chappe in 1792 in France [2]. A series of towers (shown in Fig. 3) equipped with semaphores were used for information transfer between the cities. Heliograph, a wireless solar telegraph developed by the US military in the early 1800s was based on Morse code flashes of reflected sunlight by a mirror [3]. The flashes were established by either interruption of the beam with a shutter or momentary mirror pivot. In 1880, Graham Bell introduced his photophone that was based on transmitting voice signal on a light beam [4]. The voice signal is projected toward a mirror which causes vibrations on the mirror. The mirror was then bounced by sunlight and thus, the vibrations are caught by the sunlight. At the receiver side the sunlight was received and converted back to a voice signal. The major drawback of this device is that it does not work well in cloudy weather. Optical communication did not gain much popularity till the development of Light Amplification by Stimulated Emission of Radiation (LASER). In 1970, Corning Incorporated successfully developed optical fibers for commercial purposes with low attenuation [5]. The GaAs semiconductor laser was also developed at that time for use in optical fiber cables for long distance communication. The invention of the in-fiber Bragg grating (1990) and Optical Fiber (OF) amplifier (1980) was the basis of the revolution in the field of telecommunication in the late 20th century. VLC is a type of optical communication that uses the range of frequencies from 430THz to 790 THz. In 2003 at the Nakagawa Laboratory at Keio University, Japan, transmission of data was carried out using LEDs [6].

Fig. 3. Semaphore towers in Nalbach, Germany [2].

3. Applications of VLC

Inherent features of VLC include high bandwidth, no health hazard, low power consumption and non-licensed channels that made it

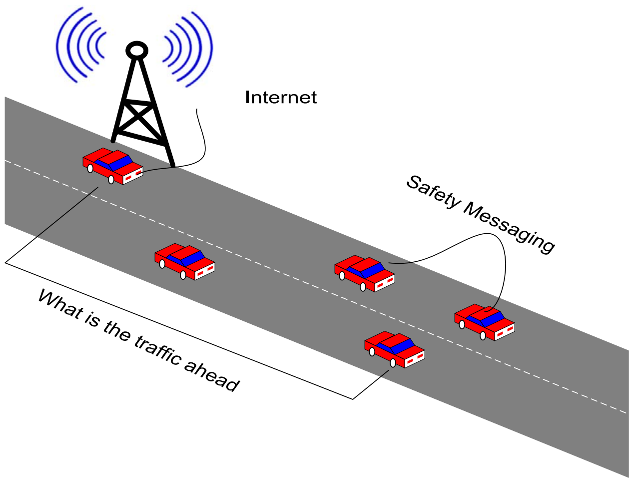


Fig. 4. VLC for vehicular networks.

attractive for practical use. Different application scenarios using VLC are as follows:

3.1. Li-Fi

In 2011, Harald Haas was the first to coin the term Light Fidelity (Li-Fi) [8,9]. Li-Fi is a high speed bi-directional fully connected, visible light wireless communication system and is analogous to Wi-Fi, which uses radio frequency for communication [10]. The Wi-Fi signals have the problem of interference with other RF signals such as its interference with pilot navigational equipment signals in aircraft [11]. Therefore, in the areas that are sensitive to electromagnetic radiation (such as aircrafts) Li-Fi can be a better solution. A Li-Fi also lends support to the Internet of Things (IoT) [7,12]. A speed up to 10Gbits/s is obtained using Li-Fi, which is 250 times more than the speed of super-fast broadband [13].

3.2. Vehicle to vehicle communication

VLC can be used for vehicular communication due to the presence of the vehicle lights and the existing traffic light infrastructure. The high priority applications indicated by the Vehicle Safety Communications Project include cooperative forward collision warning, pre-crash sensing, emergency electronic brake lights, lane change warning, stop sign movement assistant, left turn assistant, traffic signal violation warning and curve speed warning [14]. All of the high priority applications require reliable reachability with extremely low latency. Due to the extremely low allowable latency in the vehicle safety communication, a high speed visible light communication system like Li-Fi can be used as shown in Fig. 4. In [15], an outdoor VLC system using Controller Area Network (CAN) was proposed and the back lights and headlights were used in the proposed system for communication.

3.3. Underwater communication

RF waves do not travel well in sea water because of its good conductivity. Therefore, VLC communication should be used in underwater communication networks [16]. The Un Tethered Remotely Operated Vehicle (UTROV) is another application of the VLC in underwater communication. The different jobs that can be performed using UTROV include observatory maintenance of the oceans and deployment opportunity from the ships. Fig. 5 outlines the operation of the UTROV. The right pane shows the communication of the UTROV using the optical channel to a fixed infrastructure on the sea floor. In the center, the communication is achieved by UTROV using an optical channel with a ship based relay infrastructure. The left most pane shows the communication of the UTROV using low bandwidth underwater communications.

3.4. Hospitals

In hospitals, electromagnetic wave sensitive areas (such as MRI scanners) are likely to switch to VLC because it will not interfere with radio waves of the other machines [17]. In [18], a robot called HOSPI (shown in Fig. 6) was proposed that was used for transportation in hospitals. The control system enhancements in HOSPI were made using VLC installed in a building and navigational sensors of the robot.

3.5. Information displaying signboards

Signboards are often made from an array of LEDs which in turn are modulated to convey information in airports, bus stops and other places where the broadcasting of data is necessary. In [19], the sign board used for transmitting data was described. This type of sign board can be used for indications in various locations such as airports, museums and hospitals.

3.6. Visible light ID system

Visible light can be used as an ID system in different places such as buildings and subways. For example, if we are standing in room 12 in a certain building. A visible light ID system can be employed for identifying the room number and its building. Similarly a visible light ID system can be employed in subways, hospitals and airports (Fig. 7).

3.7. A Sound communication system

Red, green and blue LEDs are used for the transmission of music signals as shown in Fig. 8 [20].

3.8. Wireless Local Area Networks (WLANs)

LED based visible light communication can be used in setting up LANs. In [21], an ultra-high speed full duplex, LAN based on star topology architecture using LED visible light communication is proposed to provide a speed of more than 10Gb/s and tested for massive users. The schematic diagram of the high speed LAN is shown in Fig. 9 [21]. The reason for the design of the network using a star topology is to provide support for massive users. Fiber is used in connection with each lamp directly as shown in Fig. 9. The hybrid access protocol is used in the proposed LAN such as Time Division Multiplexing (TDM) for bidirectional VLC transmission and Frequency Division Multiplexing (FDM) for uplink and downlink fiber transmission. The results of the proposed LAN revealed its potential power of offering high speed access for massive users. In [22], a 10 Mbps VLC wireless LAN system was proposed using white LEDs. The lighting system was used for downlink and infrared light was used for up-link. The VLC wireless LAN has the potential to be used in office buildings and hospitals, which require a high level of safety.

4. Architecture of VLC

The two integral parts of the VLC system: the transmitter and receiver generally consist of three common layers. They are the

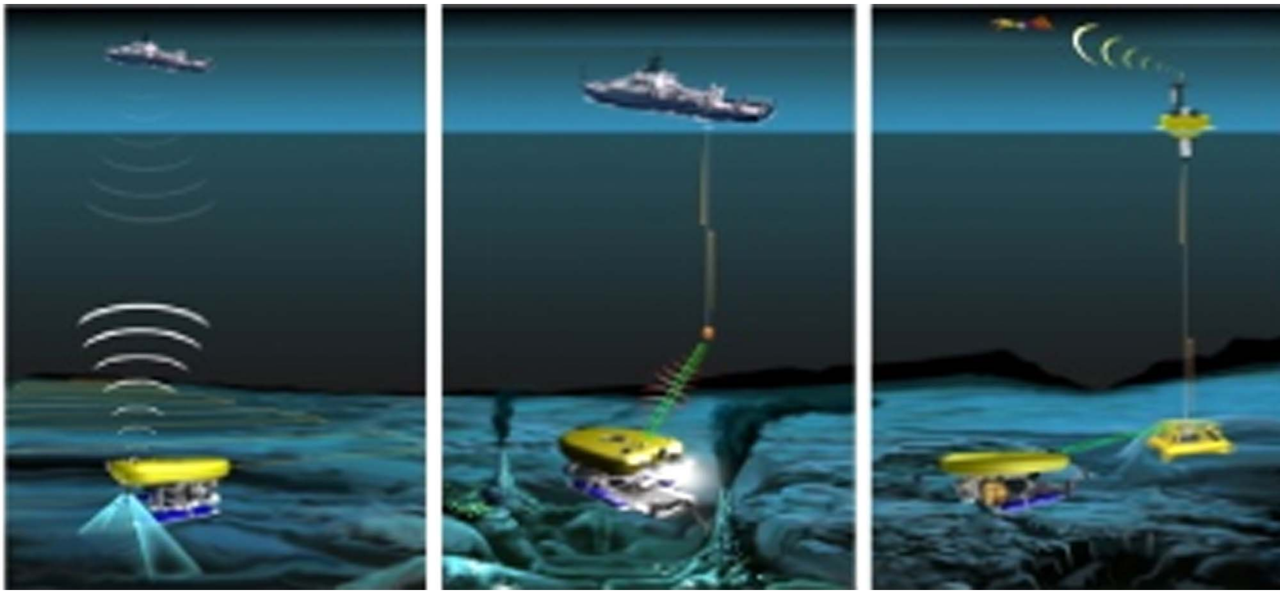


Fig. 5. Operation of UTROV [16].

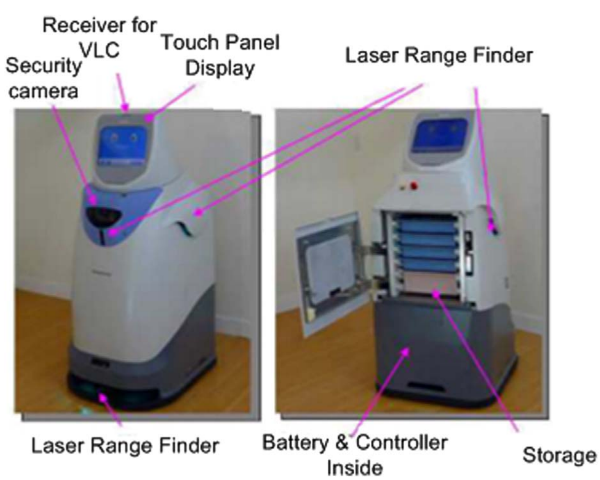


Fig. 6. HOSPI Robot [18].

Fig. 7. Prototype presented by NEC and Matsushita Electric Works [71].

physical layer, MAC layer and application layer. The reference model of the VLC communication system is shown in Fig. 11 [23]. In IEEE 802.15.7, only two layers (such as PHY and MAC) are defined for simplicity [24].

4.1. MAC layer

The tasks performed by Medium Access Control (MAC) layer include [25]:

(1) Mobility support,
(2) Dimming support,
(3) Visibility support,
(4) Security support,
(5) Schemes for mitigation of flickering,
(6) Color function support,
(7) Network beacons generation if the device is a coordinator,
(8) VPAN disassociation and association support,
(9) Providing a reliable link between peer MAC entities.

The topologies supported by the MAC layer are peer-to-peer, broadcast and star as illustrated in Fig. 10 [25]. The communication in the star topology is performed using a single centralized controller.

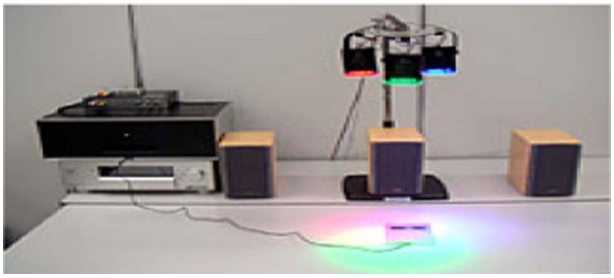


Fig. 8. VLC in a Musical System [20].

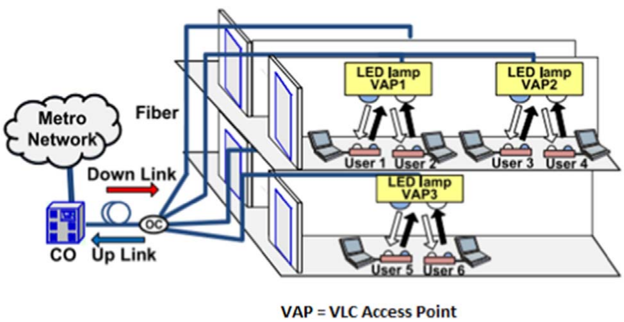


Fig. 9. The VLC network schematic diagram [21].

All the nodes communicate with each other through the centralized controller as shown in Fig. 10. The role of the coordinator in the peer-to-peer topology is performed by one of the two nodes involved in communication with each other as illustrated in Fig. 10.

4.2. Physical layer

The Physical layer provides the physical specification of the device and also, the relationship between the device and the medium. Fig. 12 shows the block diagram of the general physical layer implementation of the VLC system. First of all, the input bit stream is passed through the channel encoder (optional). Linear block codes [26], convolutional codes [27] and the state of the art turbo codes [28] can be used to enhance the performance of the VLC system. Then, the channel

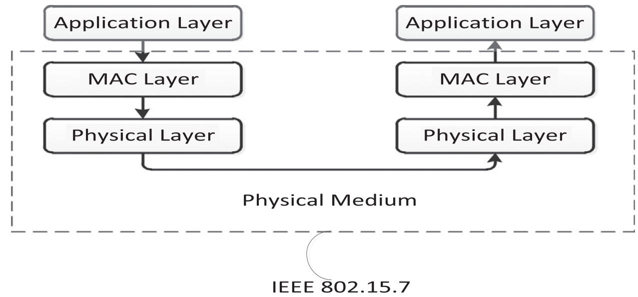


Fig. 11. Layered architecture of VLC.

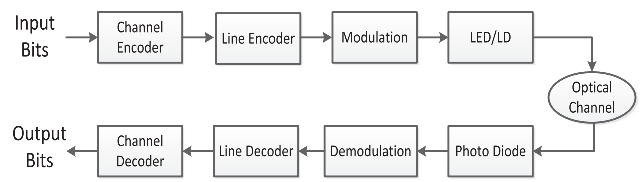


Fig. 12. Typical physical layer system model of VLC.

Table 1
PHY I operating mode specifications [25].

Modulation	RLL code	Optical clock rate	FEC		Data rate (kbps)
			Outer code (RS)	Inner code (CC)	
OOK	Manchester	200 kHz	(15,7)	1/4	11.67
			(15,11)	1/3	24.44
			(15,11)	2/3	48.89
			(15,11)	None	73.3
			None	None	100
VPPM	4B6B	400 kHz	(15,2)	None	35.56
			(15,4)	None	71.11
			(15,7)	None	124.4
			None	None	266.6

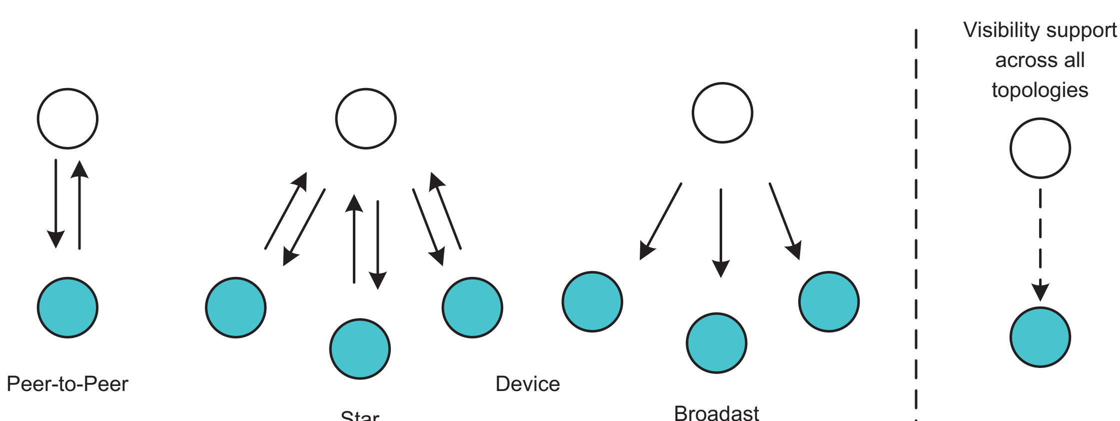


Fig. 10. Supported MAC topologies by IEEE 802.15.7 [25].

Table 2
PHY II operating mode specifications [25].

Modulation	RLL code	Optical clock rate (MHz)	FEC	Data rate (Mbps)
VPPM	4B6B	3.75	RS(64,32)	1.25
			RS(160,128)	2
		7.5	RS(64,32)	2.5
			RS(160,128)	4
			None	5
OOK	8B10B	15	RS(64,32)	6
			RS(160,128)	9.6
		30	RS(64,32)	12
			RS(160,128)	19.2
		60	RS(64,32)	24
			RS(160,128)	38.4
		120	RS(64,32)	48
			RS(160,128)	76.8
			None	96

Table 3
PHY III operating mode specifications [25].

Modulation	Optical clock rate (MHz)	FEC	Data rate (Mbps)
4-CSK	12	RS(64, 32)	12
8-CSK		RS(64, 32)	18
4-CSK	24	RS(64, 32)	24
8-CSK		RS(64, 32)	36
16-CSK		RS(64, 32)	48
8-CSK		None	72
16-CSK		None	96

encoded bit stream is passed through the line encoder to yield the encoded bit stream. After line encoding, modulation (such as ON–OFF keying, PPM and PWM, etc.) is performed and finally, the data is fed to the LED for transmission through the optical channel. In [29–31], different implementations of the visible light communication systems are given. In [29], a full-duplex bi-directional VLC system utilizing RGB LEDs and a commercially available phosphor-based LED in downlink and uplink, are proposed respectively. Wavelength Division Multiplexing (WDM) and Subcarrier Multiplexing (SCM) are used to achieve the bi-directional transmission. Furthermore, Orthogonal Frequency Division Multiplexing (OFDM) and Quadrature Amplitude Modulation (QAM) were employed to increase the data rate. The speed of the VLC system in [30] was increased to 3.75vGb/s as compared to that in [29] which was 575Mb/s downlink and 225Mb/s uplink. At the receiver side, the receiver (such as a silicon photo diode and PIN

Table 4
Comparison of phosphor based LEDs and RGB LEDs.

	RGB LEDs	Phosphor based-LEDs
Data rates	Up to 100 Mbps	Up to 50 Mbps
Price	More expensive	Less expensive
Modulation	Complex	Low complexity
Bandwidth	High	Low

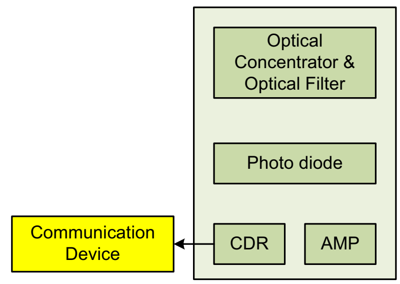


Fig. 14. Typical VLC receiver.

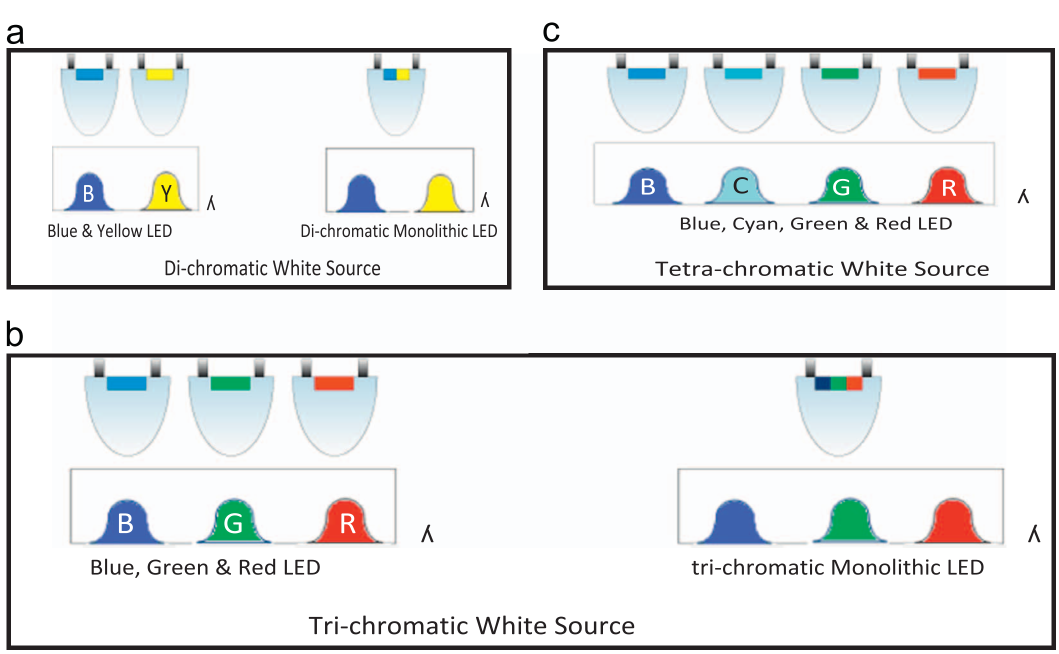


Fig. 13. White Light source based on LEDs.

photodiode) received the optical signal. After demodulation and line decoding, the bit stream passed through the channel decoder to yield the output bits.

Three different types of physical implementations of VLC are given in IEEE 802.15.7. The operating range of PHY I, PHY II and PHY III are 11.67–266.6 kbps, 1.25–96 Mbps and 12–96 Mbps, respectively. The different channel coding schemes supported by 802.15.7 are listed in Table 1, Table 2 and Table 3 [25]. Convolutional codes and Reed Solman (RS) codes are used by the PHY I because of its design for outdoor use and PHY II (intended for indoor use) provides support for Run Length Limited (RLL) code to address flicker mitigation and DC balance. The different optical rates and data rates provided by IEEE 802.15.7 are also listed in Table 1, Table 2 and Table 3.

4.3. Transmitter

The development of LEDs has made the solid state lighting an emerging field [32]. LEDs have surpassed the incandescent light sources in terms of reliability, power requirements and luminous efficiency. The efficiency of LEDs is 20 lm/W greater than the incandescent lamps efficiency [33]. LEDs and Lasers are used as transmition sources for VLC. The LED should be used when both communication and illumination have to be performed using a single device. The white light based on LEDs and wavelength converters is one of the attractive candidates for being used as the VLC source. There are different possible spectra in which white light is produced by the LEDs. The Tetra-chromatic, dichromatic and tri-chromatic modes used for generation of white light are shown in Fig. 13 [34]. The most commonly used methods for generation of white light using LEDs is trichromatic (such as red, green and blue). The advantage of using an RGB LED for white light generation is the high bandwidth and thus, high data rates. The downside of the RGB LED is their high associated complexity and difficulties in modulation. Comparison of the phosphor based LEDs and RGB LEDs are shown in Table 4. In [35–43], different methods have been adopted for characterization of the optical wireless channel. The appropriate LED is selected based on the channel model.

4.4. Receiver

The typical VLC receiver consists of an amplification circuit, optical filter and optical concentrators as shown in Fig. 14 [44,45]. The beam divergence that occurs in LEDs due to illuminating large areas results in attenuation so the optical concentrator is the device that is used to compensate this type of attenuation. In the VLC receiver, the light is detected using a photodiode and then converted to photo current. The parameter specification of the VLC will be different from that of the infrared communication because of the different wavelengths. The silicon photodiode, PIN diode and avalanche photodiode are used for VLC [46]. The avalanche photodiode has a higher gain than a PIN photodiode but at the expense of the high cost. The VLC is vulnerable to interference from other sources such as sunlight and other illumination; therefore, optical filters should be designed to mitigate the DC noise components present in the received signal. In a VLC receiver, the photodiode is generally used for reception of the VLC signals. It is better to use a photodiode in the case of a stationary receiver; however, the imaging sensor is employed instead of a photodiode because of the larger FOV in the case of mobility. Operating imaging sensors is energy expensive and slow. Therefore, a trade-off should be made between the cost, speed and complexity while considering photodiode and imaging sensors.

Table 5
Classification of IEEE 802.15.7 devices [48].

	Infrastructure	Mobile	Vehicle
Fixed coordinator	Yes	No	No
Power supply	Ample	Limited	Moderate
Form factor	Uncostrained	Constrained	Uncostrained
Light source	Intense	Weak	Intense
Physical mobility	No	Yes	Yes
Range	Short/Long	Short	Long
Data rates	High/Low	High	Low

Fig. 15. Subcarrier frequency allocation used by JEITA.

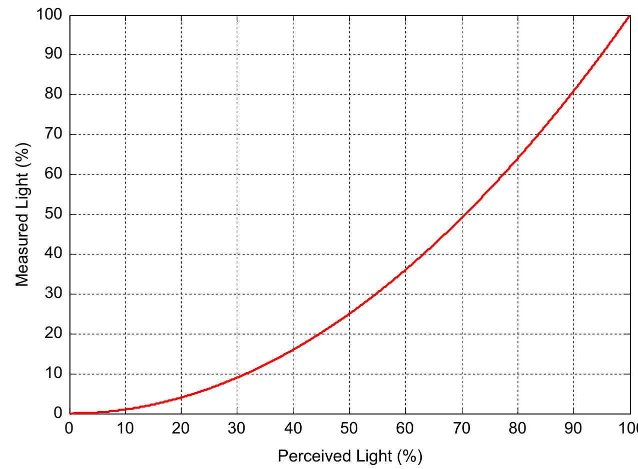


Fig. 16. Measured Vs Perceived Light by the human eye [36].

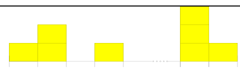
5. VLC standardization

VLC is one of the promising candidates for communication because of the rapid development of the solid state lighting. However, certain challenges that exist and must be addressed are listed as follows:

a. Integration of the VLC with the already existing communication standards such as Wi-Fi etc.
b. The issue of interference with ambient light sources.
c. The mobility issues such as handover should be properly considered in VLC.
d. To improve the communication system performance by specifying Forward Error Correction schemes.
e. Interference between the different devices using VLC is expected in the future because of an increase in the number of VLC devices.

To tackle the above problems, a standardization of VLC is imperative. The standardization of VLC has been performed by the Visible Light Communication Consortium (VLCC) in Japan and IEEE. The

Table 6
Pulse position based schemes with Q time slots and N levels [63].

Modulation	Transmitted Pattern	Number of Symbols
PPM		Q
MPPM		$\binom{Q}{K}$
EPPM		Q
MEPPM		$\binom{Q+N}{N}$

Q = Time slots N=Number of Levels

Table 7
Comparison of modulation techniques [60].

Modulation technique	Dimming support	Spectral efficiency	Flickering	Susceptibility to LED non-linearity
MPPM	Yes	< 1	Low	Low
EPPM	Yes	< 1	Low	Low
MEPPM	Yes	2–3	Very Low	Low

Japan Electronics and Information Technology Industries Association (JEITA) CP-1221, JEITA Cp-1222 and JEITA Cp-1223 are published by the VLCC [47]. The 802.15.7 is the standard completed by the IEEE for physical and MAC layers [25]. This standard is aimed at:

(1) Providing access to several hundred THz bands.
(2) Providing immunity against the electromagnetic interference.
(3) Communication that complements extra services to the existing visible light infrastructure.
(4) Specifying the FEC schemes, modulation techniques and data rates for VLC communication.
(5) The channel access mechanisms such as Contention Access Period (CAP), Contention-Free Period (CFP) and visibility support when channel access are also described.
(6) The PHY layer specifications, such as optical mapping, TX-RX turn around time, RX-TX turn around time and flicker and dimming mitigation, are also explained.

The IEEE 802.15.7 provides a minimum benchmark for the development of new products. The three different classes of devices considered for VLC are vehicle, mobile and infrastructure as indicated in Table 5 [48]. The JEITA CP-1221 standard is aimed at presenting necessary requirements and the indication level that is required to avoid the interference between different VLC devices. The wavelength range for VLC assumed by JEITA CP-1221 is 380–750 nm. JEITA uses the frequency range 1 for implementing visible light ID system as shown in Fig. 15. The inverter fluorescent lamp radiates in the frequency range 2, therefore this range is not suited for VLC communication. The frequency range 3 is used for high speed communication. In JEITA CP-1222, the subcarrier frequency 28.8 kHz with a transmission rate of 4.8 kbps is used. For error correction, cyclic redundancy check was employed.

Table 8
The center, code and chromaticity coordinates used by the seven bands used in CSK.

Band (nm)	Code	Center (nm)	(x, y)
380–478	000	429	(0.169, 0.007)
478–540	001	509	(0.011, 0.733)
540–588	010	564	(0.402, 0.597)
588–633	011	611	(0.669, 0.331)
633–679	100	656	(0.729, 0.271)
679–726	101	703	(0.734, 0.265)
726–780	110	753	(0.734, 0.265)

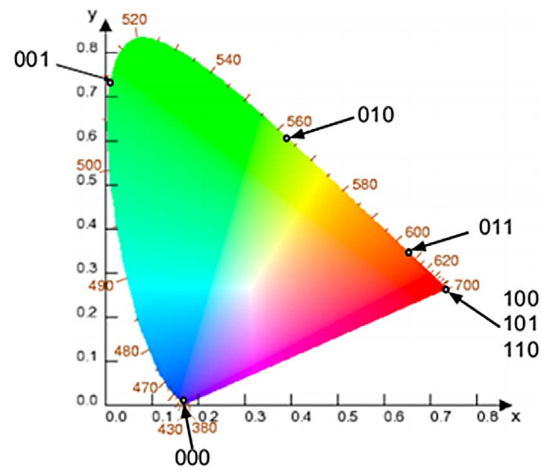


Fig. 17. Chromaticity diagram [62].

6. Modulation techniques for VLC

Modulation in VLC differs from that of RF communication because of the non-encoding feature of information in phase and amplitude of the light signal [49]. Therefore, it is clear that we cannot use amplitude and phase modulation in the case of VLC. Modulation in VLC is achieved using variations in the intensity of the light corresponding to the information in the message signal.

6.1. Factors affecting the modulation in VLC

Two factors to be considered in the design of the modulation scheme for VLC include (a) dimming and (b) flickering.

(a) Different activities require different illuminances, such as 30–100 lux that is required for normal visual activities in public locations [50]. There is a non-linear relationship (shown in Fig. 16) between the measured light and perceived light and their relation is given by:

$$\text{Perceived Light}(\%) = 100 \times \sqrt{\frac{\text{Measured Light}(\%)}{100}} \tag{1}$$

(b) The changes in brightness of the modulated light should be done in a way that it should not result in human-perceivable fluctuations. According to IEEE 802.15.7, the switching should be done at a rate faster than 200 Hz for avoiding harmful effects.

6.2. Modulation techniques

6.2.1. On–Off Keying (OOK)

In OOK [51–56], the LEDs are turned off and on according to the bits in the stream. For example, 1 is represented by the on state and 0 is represented by the off state. In OOK, the LED is not turned completely off in the off state, but the reduction in the level of intensity is performed. The main advantage of using OOK is its easy implementation. In earlier work, the VLC employing on-off keying was done using white LEDs (a combination of blue emitter and yellow phosphor). However, this suffered from the limitation of low bandwidth because of the slow time response of the yellow phosphor [54]. A data rate of 10Mbps was demonstrated in [19] using NRZ (Non Return-to-Zero) OOK with a white LED. The combination of analogue equalization with blue filtering was done to increase the data rates up to 125 Mbps and 100 Mbps respectively [55,57].

6.2.2. Pulse modulation techniques

The limitation of OOK is the low data rates, which motivated researchers to develop new modulation techniques with higher data rates. The width of the pulses (Pulse Width Modulation, PWM) varies according to dimming levels. Using the high PWM frequency, the different dimming levels can be achieved between 0% and 100% [58]. The limitation of PWM of [58] is the low data rate which was up to 4.8 Kbps. In [59], PWM was combined with Discrete Multitone (DMT) for joint communication and dimming control to achieve a data rate greater than that of [58]. A Pulse position modulation (PPM) [60] was based on the position of the pulse. The division of the symbol duration into equal intervals, t slots was done in PPM and the transmission of the pulse is done in any of the slots. As only a single pulse in each symbol period is present in the case of PPM, it suffers from the problem of low data rate; other variants of PPM were developed over time as shown in Table 6. Multi-pulse PPM (MPPM) was introduced making the PPM more spectrally efficient using the transmission of multiple pulses in each symbol-time. Expurgated PPM (EPPM) is the modified version of the PPM that was introduced to improve the performance of peak-power limited M-ary communication systems [61]. Multilevel EPPM (MEPPM) was introduced in [61] for the spectral effectiveness of the PPM because the spectral efficiency of the MPPM and EPPM was less than 1. Table 7 illustrates the comparison of different pulse modulation techniques.

6.2.3. Color Shift Keying (CSK)

CSK was proposed in IEEE 802.15.7 to enhance the data rate which was low in other modulation schemes [25]. The switching ability slows down by producing white light utilizing yellow phosphor and blue LEDs. Therefore, an alternate way to produce the white light is the utilization of three separate LEDS such Green, Blue and Red. Modulation in CSK is performed using the intensity of the three colors in an RGB LED source. CSK depends on the color space chromaticity diagram [60]. It maps all colors perceivable by eye to two chromaticity parameters such as x and y. Table 8, illustrates the human visible wavelength seven bands with their centers marked in Fig. 17.

7. Open research issues

1. Flickering is the fluctuations noticed by humans in the brightness of a light. In VLC, the modulation of the LEDs should be done in a way to avoid flickering because of its harmful effects on human health [64]. Flickering is either inter-frame flicker or intra-frame flicker depending on the nature of the brightness of the variations. The intra-frame flickering is because of the brightness difference between bits in a frame while the inter-frame flickering is due to the brightness difference between the idle period and packet frame transmission period. In PWM, the pulse train duty cycle is adjusted to controlling brightness; However, the flicker becomes more noticeable in the case of a slow data rate and a large idle period compared to the data period. Therefore, designing modulation techniques that should reduce flickering is an active research area.
2. Different levels of illuminance are required for performing different activities such as 30–100 lux that is required for performing tasks in normal places and higher illuminance up to 1000 lux in offices. Therefore, the algorithms for dimming should be designed so that the required illuminance in a particular place is fulfilled.
3. The performance of the different channel coding schemes should be investigated in VLC. As the bandwidth is very high in VLC, turbo codes with high memory orders should be used to obtain better performance. Different decoding algorithms (such as Maximum A Posteriori(MAP), Log-MAP and Max-Log MAP [65]) for component decoders should be tested and evaluated. Linear block codes such as (23,12,7) Golay code [66] can also be employed in VLC for performance enhancement.
4. Exploring the performance of the different photo diodes in VLC is also an open research area. Different photo diodes such as silicon photo diodes, PIN photodiode and avalanche photodiodes can be employed in VLC and trade-offs should be made between the performance, complexity and cost. The avalanche photodiodes have high gain while PIN diodes on the other hand feature low cost, larger active area and good performance in high noise scenarios.
5. The long run of zeros and ones results in flickering, therefore, such type of codes should be designed to prevent long run of zeros and ones and thus, avoid flickering in VLC.
6. The noise due to ambient light sources degrades the performance of the VLC system. In [67], Manchester coding was used for background noise reduction without using adaptive monitoring and feedback. Different techniques are proposed in [68–70] to reduce the background noise. Hadamard coding and Manchester coding were also used to reduce the background noise [68]. Channel coding schemes such as linear block codes, Convolutional codes and turbo codes can be preferably used for performance improvements of the VLC system. Turbo codes have better performance than linear block codes and convolutional codes, but at the cost of high overhead and complexity associated with the decoder. As the bandwidth in VLC is high therefore, it is preferable to use turbo codes in VLC. Therefore, it is an open research area, that new codes should be proposed to reduce the noise more effectively than the previously used techniques.

8. Summary

The features of high bandwidth, non-interference with the radio waves in electromagnetic sensitive areas and non-hazardous to health has made visible light communication an attractive technique for future communication. Li-Fi is 250 times faster than its analogous Wi-Fi, which uses radio frequency for communication. Potential applications of VLC include Li-Fi, visible light ID system, Hospital robots, underwater communication and traffic communication systems. All of these applications have made VLC an attractive area of research.

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