Visible Light Communication: Opportunities, Challenges and Channel Models

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ISSN: 2186-0114
http://www.IJEI.org

ARTICLE HISTORY

Received: 3 August, 2012
Revised: 21 August, 2012
Accepted: 5 September, 2012

Published online:

18 February, 2013

Vol. 2, No. 1, 2013

Abstract

Recent advancements in Solid State Lighting (SSL) have triggered research in the domain of Visible Light Communication (VLC) which enables us to use Light Emitting Diodes (LEDs) for illumination as well as low cost, high speed, power efficient and secure data communication. VLC technology is considered to be a green technology which helps in the reduction of hazardous gases emission. This paper presents a through survey on recent advancements in the domain of VLC starting from its emergence to the channel modelling.

Keywords: *light emitting diodes, visible light communication, channel modeling, radio waves.*

I. INTRODUCTION

Optical wireless communication (OWC) refers to data transmission using Infrared (IR) Wireless Communication (IrWC), ultraviolet wireless communication, VLC as well as Free Space Optics (FSO) and in contrast to radio waves. Optical wireless indeed enjoys certain advantages over radio waves which is reason for it being a popular area of research.

OWC enjoys advantages over Radio Frequency (RF). Disorders in the immunity system, neurological effects and behavior effects are linked with Radio Frequency (RF) radiations [1-2]. IR is also regulated by eye safety standards and visible light cannot be increased above the level that is comfortable for general lighting however these thresholds are lenient as compared to RF. Optical wireless communication signals do not interfere in spite of the large bandwidth available i.e. 380nm to 780 nm which is virtually unlimited free spectrum unlike radio frequency. There is no electromagnetic interference with other devices as well [3]. Light waves cannot pass through concrete or

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solid structures thus benefit from an inbuilt secure transmission of information in physical layer. Co-channel interference is an issue in radio waves and also a source of noise [4]. Concept of co or adjacent channel interference is inexistent in VLC. However an ambient light source introduces noise in the system. From the above mentioned discussion, we can say that optical wireless communication networks are the need of the hour and can provide broadband information to fixed and mobile users in small indoor vicinity in addition to its deployment in outdoor environment [5].

Thinking of a life- while eating your breakfast, you read the latest happenings in the world on your iPad through an indoor optical wireless link. Multiple heterogeneous wireless links exist in your home starting from wireless sensors for body area network to cellular network. As you move towards the washroom, an automatic handover is done and you are now connected to another wireless link. Thus wherever you roam in your home, your handheld device will automatically connect you to the most appropriate wireless network which is ultimately linked with a high speed external network [6]. Time left to achieve such a life style is no far.

A. Requirements for Future Generation Networks

After the deployment of 3G systems, researchers have observed that human needs are moving towards more and more bandwidth hungry applications. In order to fulfil the needs, fourth generation (4G) and beyond systems are being introduced realizing the fact that heterogeneous access techniques must be available. Now the race is not to connect every human with internet but everything will be wirelessly connected to the network. Requirement for connecting TV, lighting system, fans, AC, refrigerator, microwave oven etc. with the network emerged the need for the development of short range, license free wireless communication networks in which we will be able to transmit heterogeneous information at any place and any time.

B. Definition of Visible Light Communication

VLC is basically a short range optical wireless communication using LEDs for illumination and communication simultaneously. [7-8]. LEDs will be the future of modern lighting system as they enjoy many advantages over conventional lighting devices such as Mean Time before Failure (MTBF), high lighting efficiency, specific spectrum and environmental friendliness. Data transmission in VLC is done by changing the light intensity Change in amplitude is so small for a naked human eye that it is un-noticeable [9]. LED can be modulated at higher speeds which make it a suitable candidate for data transmission. Right choice of modulation scheme, selection of line coding scheme, use of equalizer at transmitter and receiver can further improve the performance of LED [10].

C. LEDs for Energy Saving

It has been observed that nearly 33% of the total electrical energy consumed is for lighting purpose [11]. Therefore it is a must that efficient lighting source must be used in order to reduce this proportion. Other than water, electrical energy is also generated from coal, gas, oil and nuclear products which are responsible for emission of CO_2 and other gases. By replacing all lighting source with LEDs, 50% of the total global power consumption for lighting will be reduced. In United States only, 760GW can be saved over a period of 20 years using LEDs. It has been estimated by Ministry of International Trade of Japan that if half of all incandescent and fluorescent lamps are replaced by LEDs in Japan then six midsized power plants will be available for providing electricity for more productive purpose in addition to the reduction of greenhouse gases[12]. Furthermore LED is classified as green technology gas it is more environmental friendly.

D. Design Challenges for VLC system

Indoor VLC can be categorized into two categories i.e. Line of Sight (LOS) and Non Line of Sight (NLOS) [13]. Both types of VLC suffer from interference from ambient light sources. Inter Symbol Interference (ISI) from multipath dispersion and synchronization at the receiver is the major problems. SNR of an optical wireless link is proportional to the square of average receiver optical signal power which means that transmission at higher power level is required as compared to electrical channel [14-15].

E. Applications

As far as LEDs based system applications are concerned, their domain is very versatile ranging from commercial purpose and academic and industrial research [16]. From inner satellite to military purpose, from hospitals (where electromagnetic interference must be avoided) to aircrafts, from lighting to automobiles, LED applications are extended [17].

II. VLC Data Transmission

A. Optical Source

Two methods are typically used for the generation of white light. Mixing specified quantities of Red, Blue and Green colour that yields white light. The major reason for not using RGB LEDs in general lighting is that the junctions that produce and green light are not as efficient as the junction that produces blue light. Efficiency of blue light is about 80% whereas it is only it is only about 60% and 30% for red and green light respectively. Furthermore this technique has certain packaging and electronic complexities which make it a less favourable technique. More attractive technique is known as phosphor based white LED. HBLEDs that produce white light do indeed produce a blue light. However, the phosphor (which is predominantly yellow) only converts part of the blue light. The converted and non-converted parts are mixed to obtain the desired shade of white.

Talking of VLC based communication system focuses on investigating two basic properties of LED i.e. luminous intensity (i.e. energy flux per solid angle) and transmitted optical power (i.e. total energy radiated from optical source). Mathematically, we can express luminous intensity I by eq. (1) [18 - 21]

$$I = \frac{d}{d\Omega}\left(K_m \int_{380}^{780} V(\lambda)\varphi_e(\lambda)d\,\lambda \right) \tag{1}$$

Where φ_e is the energy flux, $V(\lambda)$ is standard luminosity curve and λ is the maximum visibility. For a source with Lambert radiation characteristics and angle of incident $\emptyset$ [rad], horizontal luminance is expressed by eq. (2) [21]

$$E_h = I_o \cos^m(\theta) \cos(\emptyset / r^2) \quad (2)$$

Phosphor topped white LEDs radiate wideband visible light which is spread over the entire visible spectrum (shown in Figure2) and transmitted optical power is described by eq. (3)

$$P_T = \int_{\Delta_{min}}^{\Delta_{max}} \int_0^{2\pi} \varphi_e d\theta \, d\lambda \quad (3)$$

Where Δ_{max} and Δ_{min} is the sensitive curve of PD.

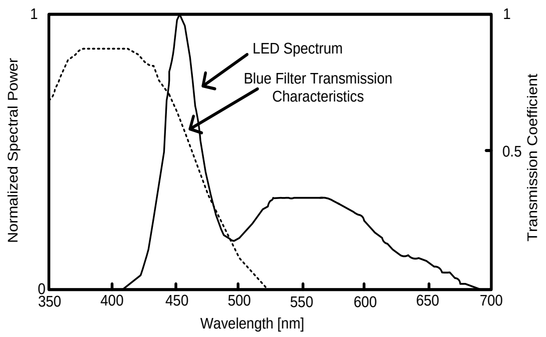

Fig. 1. Measured radiation spectrum of phosphorescent WLED with the transmission characteristic of used blue filter [22].

Revolutionary built in advantages of LED i.e. fast switching, low driving voltage compatibility with digital technology can evolve software controlled intelligent luminous and communication system [23]. Communication system challenge exists as the modulation bandwidth is limited and sluggish response of yellow phosphors converting blue light to yellow [24]. However equalization, filtering can enhance data rate. Wide band of phosphors topped white LED results in multipath dispersion which is also a challenge. Multipath bounces PDP with multiple optical source is described in [25] is given by eq. 4

$$h(t) = \sum_{n=1}^{N_{LED}} \sum_{k=0}^{\infty} h^k(t; \emptyset_n) \quad (4)$$

B. Receiver

From channel, the optical signal enters in the last stage of communication link i.e. optical receiver. Block diagram of a typical optical receiver is shown in Fig. 2.

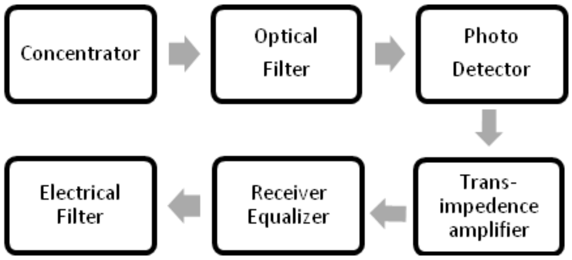

Fig. 2. Block diagram of a typical optical receiver.

Function of the concentrator is to gather more and more light to be fed to the next receiving section. For Line of Sight (LOS) and Non Line of Sight (NLOS) channels, different concentrators are used. For LOS channel, field of view (FOV) must be in such a way that it reduces light noise. For NLOS channels, compound parabolic concentrators or non-imaging hemisphere are used.

For an indoor VLC communication system, ambient light sources also fall in the visible spectrum. Optical filtering is done to narrow down the band. Filtered signal is then fed to the photo detectors which convert the optical signal into electrical signal in the form of photo current. Two kinds of photo detectors can be used. One is the photo diode (PD) and other is the image sensor. PD are the cheap solution however for sophisticated applications, image sensors are used. Photocurrent is then amplified using trans-impedance amplifiers and then equalization is done for data rate improvement which will be discussed in later section. The presence of DC signal created by the background noise can be removed by using high pass filters. The signal and ambient light induced shot noise can be modelled as eq. 5

$$\sigma_{shot}^2 = 2q\left(I_{rsignal} + I_{rambient} I_2\right)B \qquad (5)$$

Where q is the charge on electron, $I_{rsignal}$ and $I_{rambient}$ are signal and ambient light current in the photodetector respectively and I_2 is the noise bandwidth factor. Optical power received can be modelled as eq. (6) [26]

$$P_r = H\,(0).P_t \qquad (6)$$

$$H(0) = \frac{(m+1)A}{2\pi D_d^2} cos^m(\emptyset) T_s(\psi) g(\psi)\cos(\psi) \qquad (7)$$

$$for\ 0 \le \psi \le \psi_c$$

where A is the physical area of the detector in a PD, $D_d$is the distance between a transmitter and a receiver, ψ is the angle of incidence, φ is the angle of irradiance, Ts(ψ) is the gain of an optical filter, and g(ψ) is the gain of an optical concentrator. ΨC denotes the width of the field of vision at a receiver.

III. Techniques to Improve Data Rate

There are many ways to improve information rate in VLC system. Optical filtering, pre & post equalization, complex modulation techniques and optical MIMO are the commonly used techniques.

Most convenient way to improve data rate is through optical filtering in which yellow phosphor component of visible light is blocked. Equalization at transmitter (pre-equalization) and receiver (post equalization) can certainly improve the data rate. Several potential methods have been developed for equalization. Both analogue and digital techniques can be used for equalization. Analogue circuit equalization is more appropriate with On-Off Keying schemes where OFDM scheme uses equalization in digital domain [27].Equalization using a single LED as well as array of LEDs has been reported [28-30]. A successful 80Mbps short range data link has been established by [28]. Use of multiple resonant equalizers can further enhance the data rate by 10 times as proposed by [29]. 25 times more bandwidth i.e. 50 MHz has been demonstrated in which 100 Mbps NRZ Keying schemes where OFDM scheme uses equalization in digital domain [30]. RC equalizer is used which a frequency response has given by eq. 8

$$H_e(w) = \frac{1}{k} * \frac{1 + jwT}{1 + jw^{T}/_{k}} \qquad (8)$$

Where $\frac{1}{k} = \frac{R_L}{R + R_L}$ $and\ T = RC$

Adaptive equalization can be used to overcome ISI as proposed by [31]. Optical multi-input multi-output (MIMO) for achieving higher data rates is a hot area of research [32-34]. A single LED has a very small bandwidth however many LEDs can create a significant bandwidth. Challenge here is to precisely align the detector and a mobile receiver. MIMO provides the opportunity to do this [34].

IV. MODULATION TECHNIQUES IN VLC

Modulation is a key issue in VLC and resolves many issues to achieve the communication goals although create some new issues. Varieties of modulation techniques are available in the literature [35 - 39]. Table I gives a brief summary of the advantages and disadvantages of various modulation techniques.

V. CHANNEL MODELLING OF VLC

Channel modelling of VLC is a prime task and currently is an active area of research. Work from previous research is being presented in subsequent section.

A. LOS Channel Model:

For Line of Sight (LOS)channel model [40] have presented a channel model and their results give directions for the selection of LED based on received power requirements. Their model is based upon Fig. 3.

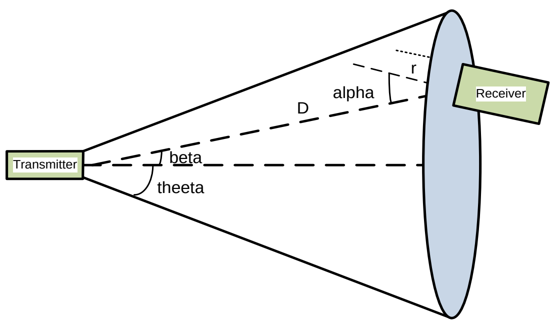

Fig. 3. LOS Channel Model.

Total transmitted luminous flux of transmitter LED (F_s) assuming spatial luminous intensity distribution is given by eq. (9).

$$F_s = I_o \int_0^{\theta_{max}} 2\pi g_s(\theta) sin\theta d\theta \quad (9)$$

Where $g_s(\theta)$ is the normalized spatial distribution and $I_o$is axial intensity. Received ingested luminous flux is given by $F_r = I_o g_s(\beta)\Omega_r$. Thus luminous path loss is given by eq. (10)

$$L_L = \frac{F_r}{F_s} = \frac{I_o g_s(\beta)\Omega_r}{I_o \int_0^{\theta_{max}} 2\pi g_s(\theta) sin\theta d\theta} \quad (10)$$

For indoor VLC system using intensity modulation and direct modulation schemes, received optical power is given by eq. (11) where P_r is given by eq. (12)

$$P_{rm} = \sum_{i=0}^{N} P_{ri} \quad (11)$$

$$P_r = \int_{\lambda_{rL}}^{\lambda_{rH}} S_r(\lambda) R_f(\lambda) d(\lambda) \quad (12)$$

Where λ_{rH} and λ_{rL} are the upper and lower wavelength bounds of the optical filter at the receiver respectively, $S_r(\lambda)$ is the source radiant power spectrum density.

B. VLC Channel Modelling with Line Coding

[41] Describes a channel model which is based upon transmitter and receiver model given by eq. (13) and (14).

$$R(\phi) = \frac{n+1}{2\pi} P_s\, cos^n(\phi) \qquad \phi\ \varepsilon \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \quad (13)$$

$$S = \{\boldsymbol{r_s}\, . \boldsymbol{\hat{n}_s}, n\} \quad (14)$$

Where $R(\phi)$ is the radiation intensity pattern, n is the number of mode of radiation pattern, $\boldsymbol{r_s}$ is the position of impulse response of optical intensity, $\hat{\boldsymbol{n}}_s$ is its orientation and n is its number mode.

TABLE I: Modulation Techniques in VLC

Modulation Technique	Advantages	Disadvantages
OOK	Good bandwidth requirement in binary modulation schemes	Suppers from multipath dispersion Threshold needed in detection
BPSK	Power Efficient	Poor bandwidth requirement
PPM and its variants (LPPM, ILPPM, SCPPM, DPPM)	High average power Minimal power consumption ILPPM good when high brightness and illumination is required SCPPM can be used to reduce low frequency and incandescent light noise DPPM does not require symbol synchronization Trellis coded PPM is an excellent option to combat multipath dispersion	Increased attenuation of multipath frequency response. DPPM has variable bit rate nature
LPAM	Reduced bandwidth requirements	Increased power penalty
LQAM	Bandwidth requirement is independent of number of sub carriers	1.5 db additional power penalty because of power wasted in combating DC
Rate Adaptive	Best when constant SNR is to be maintained	Complex
EPM	Canaviod ISI More information can be transferred them PPM	N/A

Using scaled and delayed Dirac delta function, multi bounce impulse response of LOS condition can be calculated by eq. (15)

$$h(t; S, R) = \sum_{k=0}^{\infty} h^{(k)}\,(t; S, R) \tag{15}$$

$h^{(k)}$ is the response of the light undergoing exactly k reflections. For an indoor room size of 5m*3m*3m (x,y,z), using an impulse response, final received signal is obtained mathematically by eq. (16) and BER performance of Z-HBT line coding is gives a 2-3db SNR gain as compared to conventional line coding schemes like 4B5B, HDB3 for indoor environment.

$$y(t) = \hat{x}(t) \otimes h(t) + n(t) \tag{16}$$

Where, $y(t)$ is the received signal, $\hat{x}(t)$is the line coded input, $h(t)$ is the impulse response and $n(t)$ is the additive white Gaussian noise.

C. VLC Model based on Reflection

Ding De-qiang [42] presents Lambert-Phong pattern ray tracing algorithm based upon reflection model. The intensity pattern of Lambert pattern is given by (17) and incident optical power can be expressed by eq. (18).

$$P(\theta, \emptyset, m) = \frac{P_{Tx}(m+1)}{2\pi} cos^{m}\,\theta \tag{17}$$

Where m is the Lambert exponent defining the width of the beam, P_{Tx} represents the transmitted optical beam, $\emptyset$ is the azimuth angle and θ is the angle between initial direction of the beam and the direction of maximum power.

$$P_p = \frac{A_R}{d^2} P(\theta, \emptyset, m) cos\varphi rect\left(\frac{\varphi}{FOV}\right) \quad (18)$$

Where A_R the detecting surface area of the photodiode is, d is the distance between the emitter and the receiver, FOV is the field of view and φ incident angle of incident light.

Lambert-Phong pattern is based upon identification of new reflection directions which can be divided into two steps. First is to calculate specular reflection vector R_s according to incident light vector L and unit normal vector N and is given by eq. (19). Secondly generating a random variable σ which is the angle between new reflection vector and specular reflection vector.

$$R_s = (2N.\boldsymbol{L})N - \boldsymbol{L} \quad (19)$$

Reflection intensity distribution is defined by eq. (20).

$$P_f(\sigma, \emptyset, \eta_s) = \rho \frac{P_i(m_s + 1)}{2\pi} cos^{m_s} \sigma \quad (20)$$

Where P_f is the reflection light power, P_i is the incident light power, ρ is the reflectivity of obstacles and m_s is directionality of reflection of the light. For calculating impulse response of VLC optical channel given by eq. (21), ray tracing algorithm based upon Lamber-Phong pattern is implemented for multi-source VLC system.

$$h_{VLC} = h_{LOS}(t) + h_{diffuse}(t) \quad (21)$$

Where $h_{LOS}(t)$ is the impulse response induced by LOS signal. Simulation results show the enhancement in the channel performance especially the bandwidth in addition to decrease in time spread and improved power efficiency.

VI. IEEE 802.15.7 Standard

IEEE calls for contribution in year 2009 for Short-Range Wireless Optical Communication Using Visible Light. In September 2011, IEEE defines standards for a Physical and MAC layer for short-range optical wireless communications using visible light in optically transparent media. The standard can deliver data rates sufficient to support audio and video multimedia services and also takes care of noise and interference from light sources. The purpose of this standard is to provide a global standard for short-range optical wireless communication using visible light by providing access to several hundred THz of unlicensed band. IEEE 802.15.7 standard can be summarized by Table II [43].

TABLE II. IEEE 802.15.7 Summary

Entity	Characteristics
MAC Supported Topology	- Star - P2P - Broadcast
Addressing	- 16 bit - 64 bit
Collision Avoidance Scheme	Yes - Scheduled - Slotted random access with collision avoidance
Acknowledgement	Yes
Device Classification	- Infrastructure - Mobile - Vehicle
Modulation Scheme	- OOK - VPPM - CSK
PHY Frame Structure	|Preamble|PHY Header| HCS| Optional Fields| PSDU|
Multiplexing	FDM
Data Transfer Model	03
Clock Rate Selection	Multiple from 200 KHz to 120 MHz
Cryptographic	Symmetric Key

Mechanism	Cryptography
MAC Protocol Specifications	- Generating and Synchronizing Network Beacon - Supporting VPAN Association - Color Function - Visibility - Dimming - Visual Indication - Device Security - Mobility and Reliable Link
Contention Period	- Contention Access Period - Contention Free Period
Channel Scan	- Active - Passive
Synchronization	- With Beacon - Without Beacon
Multiple Channel Usage	Supported
MAC Frame Format	|Frame Control| Sequence No.| Destination VPAN Identifier| Destination Address| Source VPAN Identifier| Source Address| Auxiliary Security Header| Frame Payload| FCS|
Max. Error Tolerance for Multiple Optical Source	Not more than 12.5% of the clock period
Clear Channel Assessment (CCA)	- Mode 1: Energy Above Threshold - Mode 2: Carrier Sense - Mode 3: Carrier Sense with Energy Threshold
Data Mode of PHY	- Single - Packed - Burst - Dimmed OOK

VII. Conclusion

From the above discussion, it can be concluded that VLC is a promising technology not only to increase not only the capacity of indoor wireless communication but also the security. Market penetration of white LEDs is very rapid and they can be used both for lighting and communication. VLC provides a cost effective technique of duplex communication not only for home users but can also satisfy the requirements of a small LAN. In this paper, some VLC channel models have also been presented and channel characteristics have been described. No doubt, there are many challenges which are being faced by the researchers such as ambient noise, ISI, improvement in SNR etc. yet VLC presents a realistic and promising supplement technology to radio communication.

Acknowledgments

Authors would like to thank National Electronics and Computer Technology Centre (NECTEC), Thailand for funding this project.

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