Short Range Visible Light Communication: LED Based Applications

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Abstract. Visible Light Communication (VLC) systems are capable of providing significantly higher data rates compared to traditional wireless technologies. Apart from high data rate, other advantages offered by VLC are license free spectrum, improved security, and no environmental radiation hazards. Light Emmiting Diode (LED) based VLC systems allow visible light to be used for indoor communications and high-precision positioning. But widespread deployment of VLC is limited due to several challenges such as layout modification to the current infrastructure, limited bandwidth of optical source, and the need to combat problems caused by ambient light and shadowing in VLC applications. This paper explores the current state of VLC and its various short range applications and presents an inclusive review on design challenges and their potential solutions.

Keywords: VLC · Communication · LED · OOK · PPM · MIMO · Image sensor

1 Introduction

Over the last decade advances in solid-state-engineering has led to the design and development of efficient optical devices in visible optical spectrum ranging from 380–700 nm for deployment in optical wireless communication (OWC) systems known as visible light communication (VLC) systems [1]. VLC systems have the ability to leverage existing illumination installations for the transmission of information. VLC sources are omnipresent, so they can be made to achieve ubiquitous communication networking without the need for additional infrastructure deployment. VLC based systems provide better electromagnetic compatibility

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(EMC) in any environment as optical signal does not interfere with the existing electronic systems. Consequently, these systems can be deployed in sensitive regions having EMC restrictions like hospitals, petrochemical industrial plants etc. VLC can be deployed in various systems due to its advantages in terms of license free spectrum, inherent security, cheaper optical components, less electrical power requirement, improved electromagnetic compatibility and significantly higher data rates in comparison with existing system that are based on Radio frequency wireless technologies [2]. Table 1 depicts a Parameter comparative of VLC and RF systems. LEDs are the preferred optical sources for most of the VLC applications as these are used for illumination purpose as well. However, widespread deployment of VLC systems is still limited due to several technological challenges that need to be addressed [3].

Table 1. Parameter Comparison of VLC and RF Systems

S.No.	Property	Short Range VLC Systems	RF Systems
1	Bandwidth/Frequency	Unlimited, 400–700 nm free to use	Limited, Licensed Frequency range
2	Detection	Incoherent	Coherent/Incoherent
3	Electromagnetic Hazard	No	Yes
4	Line of Sight	Required for most applications	No
5	Distance	Short	Short to Long
6	Security	Good	Easily Compromised without additional measures
7	Standardization	In progress (IEEE 802. 15. 7) PHY and MAC standard Completed	In Place
8	Services	Illumination and Communication	Communication
9	Major Noise Sources	Sun Light and Ambient Light	All electrical/electronic appliances

Various efforts are being made to incorporate VLC in mainstream communication systems due to its higher data rates and several other potential advantages. Many advanced concepts of physical layer that are already implemented in RF systems have been recently explored for possible inclusion in the design of VLC systems. Techniques such as OFDM, MIMO communication, adaptive transmission which provide significant benefits in conventional wireless systems need to be adapted for VLC systems. Further, the release of the IEEE 802.15.7 standard [4] has provided a momentum to the research in the area of VLC.

This paper presents an assessment of the current state of VLC technology and technical challenges involved in its implementation. Section 2 outlines basic

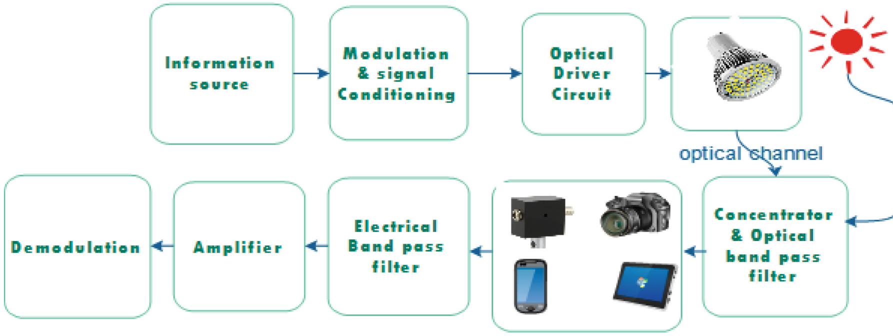

Fig. 1. Block Diagram of a Generalized VLC System.

system design of VLC configuration including the details on system components. Section 3 discusses implementation process describing the transmitters and various modulation techniques that can be utilized with VLC systems and design challenges in its implementation, Sect. 4 presents various VLC applications and possible solutions. Section 5 concludes with the discussion.

2 Overview of VLC System

Figure 1 depicts generalized block diagram of a typical VLC system. Optical source power output is modulated according to the information signal by appropriately changing the input current. Optical source output after propagation through channel reaches the receiver end and it is incident on an optical system consisting of 1) concentrator to focus incident light onto the detector and 2) an optical filter that selects optical signal and rejects noise component.

2.1 Receiver

Two types of receivers can be used in VLC systems a) non-imaging (photodiode) and b) image sensor. Non-imaging receiver uses a number of independent photodiodes with narrow Field of View (FOV). Each photodiode is equipped with its individual lens system. Very high data rates can be achieved through this lens-photodiode assembly when worked with precise alignment. Image sensor typically has an assembly of single projection lens and an array of photodiodes. Projection lens increases the field of view and this eliminates the requirement of precise alignment of transmitter and receiver. In most of the VLC applications PIN Photodiodes are used in optical receivers due to their significantly higher throughput and simple hardware implementation. VLC systems are generally operated in three system configurations;

– Directed Line of Sight
– Non-directed Line of Sight

– Non-directed Non- Line of Sight.

Some specific applications may require hybrid variation of these configurations. A particular link configuration is chosen on the basis of bit rate, coverage range, shadowing, mobility and need of alignment.

Directed LOS. Directed LOS systems as shown in Fig. 2 use directional transmitter to concentrate optical signals in a very narrow beam. Major advantages of this configuration are low power requirements at the transmitter level, negligible multipath-induced signal degradation and high data rates. Directed LOS links must have accurately aligned transmitter and receiver. This requires complex tracking and limits the user mobility. Further, these systems suffer from shadowing. Due to the above mentioned limitations this configuration may not be the best configuration for applications involving mobility. However, this configuration is especially suited for point-to-point communication links.

Non-directed LOS. This configuration requires alignment between transmitter and receiver as depicted in Fig. 3. VLC systems employing this configurations require higher transmit power and suffer from inter-symbol interference due to multipath propagation; which increases sharply with the increase in coverage area. Further these systems do not have lens assembly at the receiver; therefore received optical signal is small, at the same time, a much higher amount of ambient light noise is collected; this drastically reduces the signal-to-noise ratio.

Non-directed Non-LOS Configuration. This configuration shown in Fig. 4 is also known as diffused configuration. Optical signal from a wide beam transmitter pointing towards ceiling is spread uniformly using reflective surface of ceiling. No alignment is required between transmitter and receiver since it employs a wide FOV receiver. Transmitted signal reaches the receiver through multiple diffuse reflections in indoor environment. This is the most robust and flexible VLC configuration since it can operate even when the LoS path between transmitter and receiver is not feasible. However, Inter Symbol Interference (ISI) due to multi path propagation in these systems may result in poor power efficiency. Another drawback is much-reduced data rate compared to directed LOS configuration.

3 Enabling Technology and Technical Challenges

Ever increasing demand for efficient communication requires potential technologies like VLC to support intelligent communication. But VLC has its own share of design challenges that are discussed in this section.

3.1 Light Source

Optical source used in VLC systems must meet the standards for lighting for successful integration in present lighting infrastructure. Apart from this these

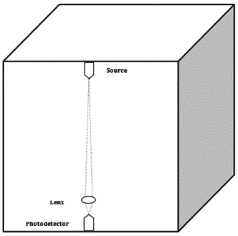

Fig. 2. Directed LoS

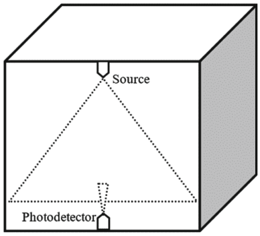

Fig. 3. Non-directed LOS

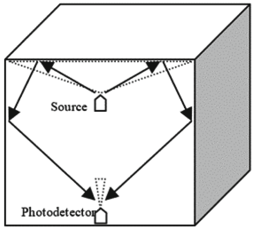

Fig. 4. Non-directed non-LOS

devices must have switching capacity at high speeds. This feature allows the optical source to send information encoded in the intensity of the light emitted when a certain area is illuminated. VLC systems usually employ White LED (WLED) as optical source and there are two types of LEDs that produce white light.

Inorganic White Light Semiconductor LEDs. Phosphor based White LEDs usually employ a blue emitting gallium nitride (GaN). They are coated with color converting phosphor (Cerium doped Yttrium Aluminum Garnet) and can be employed for illumination purpose to obtain white light. It is also cost effective and easily available. However, the phosphor coating limits the LED switching speed. In other type of white LEDs red, green and blue wavelengths are generated independently inside the LED array. The combined effect of these three components gets white light. This trichromatic LED is preferred for VLC communication applications for faster rise time resulting in higher bandwidth enabling the use of Color Shift Keying.

Organic LEDs (OLEDs). These LEDs are made from either small molecules or polymeric organic semiconductors. Polymer based OLEDs have several advantages over inorganic LEDs, namely; large photoactive areas, low temperature operation, ultra-low costs and improved mechanical flexibility. Major limitation for VLC systems is maximum switching speed of optical source. LEDs for illumination purpose are required to provide adequate output power and hence active area of these LEDs is significantly large resulting in high values of capacitance thereby limiting maximum frequency of operation in communication. MicroLEDs [5], resonant cavity LEDs are among the emerging electronic optical sources that can efficiently perform operations of illumination and data communication simultaneously. They are being investigated for possible deployment in VLC systems. For efficient data transmission in a VLC system, it is required that optical source should remain switched on during the process of transmission. The dimming allows the proper functioning of VLC communication link even when the light source is switched off or brightness is arbitrarily reduced according to the user preferences [6–8].

3.2 Modulation Techniques

Selection of right modulation scheme is one of the most critical issues in designing the VLC systems since, modulation scheme determines system's resilience to channel impairments such as multipath propagation, ambient light interference, and flicker noise. As discussed in previous section VLC optical sources are bandwidth limited. Further emitted optical power cannot be negative thus; Modulation techniques for VLC systems should satisfy the non-negativity constraint. Therefore the choice of modulations techniques is especially limited in VLC systems. In this section, the performance and suitability of various modulation schemes for VLC is discussed. Modulation techniques can be broadly categorized as: a) Single-carrier (SC) modulation and b) Multiple-subcarrier modulation techniques c) colour domain modulation techniques.

Single-Carrier Modulation Techniques. These schemes utilize one sinusoidal wave for data transmission. Single carrier modulation techniques are suitable for low to medium data rate applications. ASK (OOK) and PPM are two widely utilized SC modulation techniques for VLC. Performance of ASK (OOK) degrades rapidly with increasing noise. Since VLC systems are generally operated in noisy environment hence, the most challenging problem is the design of equalizers to reduce noise. Generation of PPM is more complex compared to OOK. Symbol-level and slot-level synchronization is required in PPM to decode the transmitted signal at the receiver end. This makes the implementation of PPM complex. PPM technique is mainly used in applications with no multipath interference.

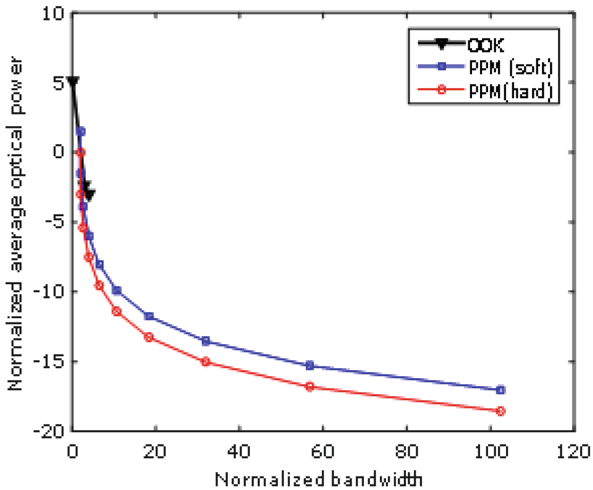

Fig. 5. Optical power requirement (normalized) for OOK, PPM [9].

Power efficiency and bandwidth requirement may be used as common parameters to evaluate the overall efficiency of modulation schemes. Figure 5 displays the comparison of OOK and PPM on these parameters generated using the analysis of S Randel et al. [9]. It may be observed clearly from the Fig. 5 that OOK outperforms PPM in terms of both the parameters and hence it is most widely used technique for VLC systems. Another variation of PPM known as variable pulse-position modulation (VPPM) supports dimming control by utilization of pulse width modulation.

Colour Domain Modulation Techniques. Colour domain modulation techniques are VLC specific modulation schemes that exploit human eye's limited Spectral Power Distribution (SPD) distinguishability. Human eyesight suffers from metamerism, i.e. light sources with different SPDs may appear same in colour. In human eye, three types of cone receptors are present: short, medium and long, which correspond to blue, green and red colour respectively. Human eye perceives the colour by mapping physically produced colour to the sensation produced by the three type of cone receptors. International Commission on Illumination in 1931 proposed of colour space that is defined by a set of three primary unitless colours. These are represented by X Y Z tristimulus values [10]. Human eye perceives colours as a linear combination of three primary colours given by eq 1

$$[X, Y, Z] = \int_{\lambda_{380}}^{\lambda_{780}} P(\lambda)[r(\lambda), b(\lambda), g(\lambda)]d\lambda \tag{1}$$

where P is SPD of source being used and $r(\lambda), b(\lambda), g(\lambda)$ are colour matching functions representing sensitivity of human visual system.

Metameric modulation is a color domain approach suitable for VLC systems. It encodes data signal to combination of LEDs having differing SPDs that are distinguishable at the receiver but is not perceived by human eye. Metameric modulation has limited color flicker effects compared to CSK. Colour tunable LEDs such as RGB LEDs are capable of producing different colours based on the input signal applied on each LED component. In Colour Shift Keying (CSK), overall intensity of the output colour is kept constant to avoid flickering. The relative intensities of each colour is varied according to the transmitted bit sequence [11]. For human eye this light appears white, but optical receivers are able to detect individual color variations.

Multiple-Subcarrier Modulation. Multicarrier modulation techniques divide the available bandwidth into many subchannels and send the data as parallel streams. Therefore these modulation schemes offer high data rates and can adapt system performance according to different channel conditions. Orthogonal Frequency Division Multiplexing (OFDM) is undoubtedly most utilized multiple subcarrier modulation schemes for conventional RF wireless systems. In OFDM parallel data is transmitted through orthogonal subcarriers. This can also be used for VLC applications. However, optical systems cannot detect phase information; thus optical-OFDM is somewhat different from its RF counterpart. Furthermore, Optical OFDM (OOFDM) techniques need to allow compensation for the nonlinear characteristics of the LEDs [12,13]. There are two unipolar OFDM schemes for implementing OFDM IM/DD optical systems, these are:

DC-Biased Optical OFDM (DCO-OFDM): This modulation technique adds a DC bias into the signal, optimum bias is usually determined by Constellation size. This addition leads to increase in overall energy requirement [13].

Asymmetrically Clipped Optical OFDM (ACO- OFDM): In ACO-OFDM there is no negative going signal as the bipolar OFDM signal is clipped at 0. System modulates either even or odd frequency subcarriers and the other frequency subcarriers are set to 0 [14].

OOFDM techniques are sensitive to Doppler shift and frequency synchronization problems. Apart from these techniques other explored variation to OFDM are unipolar OFDM, Flip-OFDM, and spectrally-factorized optical OFDM etc. All these techniques suffer from certain loss in spectral efficiency.

Non-orthogonal Multiple Access (NOMA). NOMA is one of the most extensively researched multiple-access techniques for integration into VLC systems [15–17].

NOMA is an excellent choice particularly for indoor VLC systems due to the following reasons:

- In NOMA-VLC systems, power domain multiplexing is utilized to accommodate multiple users within the same spectral resources thus providing great spectral efficiency.
- In indoor VLC systems, the number of users that a particular cell needs to accommodate for NOMA to function properly is small because VLC systems in indoor environments are often deployed in specific zones, so, the number of users within the range of a cell is limited.
- The channel remains relatively constant in indoor environments and this simplifies channel estimation. Therefore NOMA based VLC systems using the known Channel State Information (CSI) can efficiently perform load distribution at the transmitter and interference cancellation at the receiver.

3.3 Multiple Input Multiple Output (MIMO) VLC Systems

MIMO technology has been utilized with great effect in RF communications to achieve diversity benefits. Lot of research is being undertaken to apply the same in VLC, however, there are several significant differences when considering MIMO technology for optical systems. The optical MIMO channel inputs and outputs are not complex numbers but real intensities. Furthermore, the dominant noise mechanism in optical systems is signal-dependent shot noise which is not additive in nature.

If h(t) denotes the impulse response of the IM/DD channel. Then h(t) may be assumed stationary as it varies only when emitter, receiver are moved significantly. At the receiver, most dominant noise mechanism is shot noise due to background illumination. Shot noise has high intensity and it may be assured to be independent of distance d(t) [18]. When little ambient light is present then component of shot noise may be ignored and receiver preamplifier noise may be seen as dominant noise component. Assuming shot noise and receivers pre-amplifier noise as signal independent and white Gaussian n(t), if R denotes detector responsivity, instantaneous output current at the receiver is given by Eq. 2:

$$y(t) = Rd(t) \otimes h(t) + n(t) \tag{2}$$

here the "$\otimes$" denotes convolution operation.

Non-imaging MIMO VLC System. Non-imaging MIMO VLC system's impulse response is derived by treating each LED array as a single optical source. These individual light sources emit in Lambertian beam transmission pattern [19]. Considering the i^{th} receiver antenna and j^{th} transmitter antenna, impulse response h_{ij}, is:

$$h_{ij} = \frac{(m_j + 1)\, A_i}{2\pi D_{i,j}^2} \cos\alpha_{ij} Cos_j^m\left(\beta_{ij}\right) \tag{3}$$

for j^{th} transmitter m_j denotes the order of Lambertian radiation pattern, D_{ij} is distance between j^{th} transmitter and i^{th}receiver, α_{ij} and β_{ij} are the angle of incidence and angle of emission for i^{th} receiver and j^{th}transmitter respectively, A_i is the active area, and the number of transmitting and receiving elements are N_t and N_r respectively. ψ_{ij} is the field of view (FOV) of i^{th} receiver. Channel matrix is given by $H = [h_{ij}]$ Where h_{ij} is given by Eq. 3 under the condition $0 \leq \alpha_{ij} \leq \psi_{ij}$ otherwise it's value is 0.

Imaging MIMO VLC System. In imaging MIMO systems each LED and detector needs to be strictly aligned, this makes system implementation difficult. Non-imaging MIMO systems on the other hand project information to be transmitted onto the sensor array, thus it may fall on one or several sensing elements, so these systems have tolerance to the misalignment as alignment requirement is less stringent. Such a system is defined by Eq. 4 and 5, 6 and 7

$$h^{'} = \alpha_{ij} h_j \tag{4}$$

where

$$\alpha_{ij} = \frac{AI_{i,j}}{\sum_{p=1}^{N_r} A_{p,j}} \tag{5}$$

here $h^{'}$ represents the DC gain from transmitting antenna j to each receiving sensor antenna i , $AI_{i,j}$ and α_{ij} represent the area and the proportion of the energy of transmitting light source j incident on receiving pixel i respectively [20]. For emitted and received spatial optical intensity distribution $i_T(x, y)$ and $i_R(x, y)$, the point-spread function $h_{im}(x, y)$ we may write their relation as Eq. 6 and 7

$$i_T' = \frac{1}{M} i_T \left(\frac{x}{M}, \frac{y}{M}\right) \tag{6}$$

$$i_R(x, y) = h_{im}(x, y) \otimes i_T'(x, y) \tag{7}$$

Practically, diffraction due to finite aperture of the imaging components limit $h_{im}(x, y)$. These receivers can be used to create high data-rate MIMO link. Efficiency of thus created MIMO-channel depends on advanced image processing techniques. Sung et al. demonstrated the use of Charge Coupled Device(CCD) as image sensor receiver [20]. All the mobile devices e.g. Smartphones/tablets/ipads etc. are equipped with high resolution cameras which is essentially an image sensor. This gives a very promising future for VLC communication as it converts our mobile devices easily into VLC receivers. However, mobile camera can capture only limited number of frames per second (fps). Consequently, image sensor based systems give very limited data-rate (kbps).

4 Application Specific Technical Issues and Their Potential Solutions

In this section, application specific technical challenges in VLC are discussed that emerge after taking into account the particularities of the application scenario. Most of the practical implementations in VLC technology are point to point unidirectional communication links [21]. Short range VLC links with efficient bidirectional transmission may be utilized to establish wireless personal area network (WPAN) and wireless body area network (WBAN). A VLC-WPAN must fulfill QoS requirements for different kinds of service. Thus QoS provisioning and achieving full duplex communication may be considered as key design issues in short distance VLC systems. Another limitation, caused by power requirements of LED as a source can be overcome by the use of the already existing RF infrastructure for uplink transmission [22]. Another interesting short range VLC application is in airplanes, where passengers can get internet access with the help of LED lamps installed as reading lights as shown in Fig. 6.

Major advantages offered by VLC in underwater communication are device portability and data rate improvement. As shown in Fig. 7 Optical signal divergence is relatively less than currently prevalent RF and Sound signal. To combat loss of link in propagation environment is a major challenge faced by underwater VLC systems [23]. Other applications of VLC include indoor family broadcasting, hospitals, shopping malls, stadiums, music halls, ancient monuments/museums, etc.

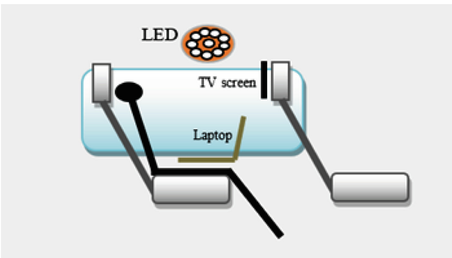

Fig. 6. VLC in Aircraft.

Fig. 7. Underwater Communication using VLC

VLC offers several attractive benefits, and it is suitable technique for providing wireless healthcare service particularly in RF restricted healthcare institutions [24]. Managing ambient noise and interference is one of the most important consideration in indoor VLC applications. Ambient noise can be reduced by placing the VLC receiver in such that it is facing away from strong interference source; because diffused indirect reflectance of visible light is not significant. For indoor transmission purposes even lower power transmission can be used as number of strong noise sources are limited. One more interesting scenario is to use different colours to cater different users to avoid noise. Several researchers have [25] proposed indoor broadband broadcasting systems which integrate Power line communication (PLC) with Visible Light Communication. In a combined PLC-VLC system LED lights get power and networking information both from PLC network. This technique ensures minimum modification in the current infrastructure.

5 Conclusion

Visible Light Communication definitely has very promising future, but it also has its share of design challenges. This paper provided a quick overview of VLC systems for investigating VLC as a potential research area. VLC systems are categorized based on LoS characteristics as Directed LoS, Non-directed LoS and Non-directed non LoS. Both Inorganic white LEDs and Organic LEDs can be utilized for data generation in VLC systems. VLC sources can work with Single Carrier modulation, Multiple-carrier modulation technique and color domain modulation technique. In addition, efficient mechanisms for dimming support are essential for widespread deployment of VLC systems. Optical MIMO technology holds promise for improving the performance and capacity of VLC systems. A lot of research is focused on improving LED performance through use of advanced LED materials, efficient driver circuit and novel device architectures. Another issue is the efficient transceiver design to achieve full duplex communication, where researchers are exploring various antenna designs and techniques to mitigate self-interference in VLC transceivers.

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