A SURVEY OF WIRELESS COMMUNICATION USING VISIBLE LIGHT

M. V. Bhalerao[1], S. S. Sonavane[2], V. Kumar[3]

[1]Asst. Prof., E&TC Engg., PVG's, College of Engineering, Nashik, Maharashtra, India
[2] Professor, E&TC Engg., DYP School of Engineering, Pune, Maharashtra, India
[3] Professor, Electronics Engg., Indian School of Mines, Dhanbad, Jharkhand, India

ABSTRACT

This paper introduces the concept of visible light communication (VLC). The urgent need of VLC is to overcome the problems faced in RF communication. Unlike existing methods of wireless communication, the visible light portion of the electromagnetic frequency spectrum is used in VLC to transmit information. This is similar to established forms of wireless communication such as Wi-Fi which uses radio frequency (RF) signals to transmit information. In VLC, communication takes place by modulating the intensity of the LED light in such a way that it is undetectable to the human eyes. A photo sensitive detector which demodulates the light signal into electronic form is used as a receiver. This work provides an extensive overview of applications and design challenges for VLC, challenge for indoor communication, uplink channel and at each layer of the communication protocol stack.

KEYWORDS: *Visible Light communication (VLC), Line Of Sight (LOS), Physical Layer (PHY), Optical Wireless Media Access Control (OWMAC), Optical Wireless Logical Link Control (OWLLC).*

I. INTRODUCTION

Optical Communication Engineering has a long history as compared to RF engineering. Even though the E-smog problem was known, RF technologies were ruthlessly applied and through misuse have turned into a risk to life. Using light for the dissemination of news in the natural form of visual communication in the past, human could communicate across great distances virtually at light speed via beacon fires, smoke signals, signal markers and light houses. The first experiment of VLC was done by Graham Bell in 1880, whose system was called as Photophone [1] [2].

In VLC, communication takes place by modulating the intensity of the LED light in such a way that it is undetectable to the human eyes. A photo sensitive detector which demodulates the light signal into electronic form is used as a receiver. VLC is a category of Optical Wireless Communications (OWC). OWC includes Infrared (IR) and Ultra Violet (UV) communications as well as visible light. VLC is unique from IR and UV because the same visible light energy used for illumination may also be used for communication [3][4].

Visible light is a constant stream of photons emitted from the LED light bulb when a constant current is applied to LED light bulb. The output intensity of the light dims up and down with respective up and down current flowing through LED bulb. LED bulbs are semi-conductor devices [5]. When the current varies at extremely high speeds and hence the optical output is variable which can be detected by a Photo Diode (PD) but which are undetectable to the human eye[6]. High speed data can be transmitted from an LED light bulb using this technique. RF communication requires complex transrecievers with antennas, whereas VLC is much simpler and use direct modulation methods similar to low cost IR communications devices such as remote control units. IR communication is limited in power due to human eye safety [7]. LED light bulbs have high intensities and can achieve very large data rates [4]. The Government of US and UK had decided to replace all inefficient high power consuming incandescent fluorescent light bulbs/tubes with highly efficient and low power consuming LEDs [8].

This paper departs from current technology and introduces the concept of VLC, where the communication took place by LEDs and photo detector devices in the Visible Light electromagnetic spectrum. VLC can address the cited shortcomings of current existing wireless sensor networks in the following ways:

Ability: The visible light spectrum bandwidth is 10,000 more than RF spectrum and also unlicensed with free to use. VLC can achieve about 1000x the data density of Wi-Fi because visible light can be well contained in a tight illumination area whereas RF tends to spread out and cause interference. Very high data rates can be achieved in VLC due to low interference, high device bandwidths and high intensity optical output. RF is invisible and makes arrangement more complex. In VLC capacity planning is simple since there tends to be lighting infrastructure, where user wishes to communicate and good signal power can be accurately seen [4].

Efficiency: VLC is a low cost solution as it requires fewer components than radio technology. LED illumination is efficient and the data transmission requires negligible additional power[4]. VLC works well in underwater communication but RF transmission and propagation in water is extremely difficult [9].

Safety: Life on earth has evolved through exposure to visible light. There are no known safety or health concerns for this technology. The transmission of light avoids the use of radio antenna systems that can cause sparks which are dangerous in certain environments [4].

Security: It is difficult to eves drop on VLC signals since the signal is confined to the closely defined illumination area and will not travel through walls. Data may be directed from one device to another and the user can see where the data is going, there is no need for additional security such as pairing for RF interconnections such as Bluetooth [4].

While the benefits of VLC should be clear from the above, there are a number of research challenges that must be addressed to make them feasible.

II. MANUSCRIPT ORGANIZATION

The paper organization can be described as the following: in the third section a applications of VLC are classified and described in details, while in fourth section, the challenges to VLC is described. Need of VLC is explained in section V, communication architecture of VLC is explained in section VI and future work in VLC is explained in section VII. Finally, conclusions about the improvements and research challenges in this work are presented in the Section VIII.

III. APPLICATIONS

Current and potential VLC applications are classified into six categories: Domestic, Transport, Hospitals, Industrials, Public sector, and Homeland Security Defense.

Domestic: RF technology is relatively expensive and difficult to implement. VLC not occupying RF spectrum as well as neither need an expensive RF band license nor produces E-smog. VLC is a strong alternative for wireless access in RF pollution awareness and RF forbidden situations. Any lighting lamps can be used to provide VLC hotspots and the same communications and sensor infrastructure can be used to monitor and control lighting and data. In figure 1 Laptops, computers, printers, mobile phones, tablets and other mobile devices are interconnected using VLC. Over short range links it provides security via the visible pairing method and also gives very high data rates.

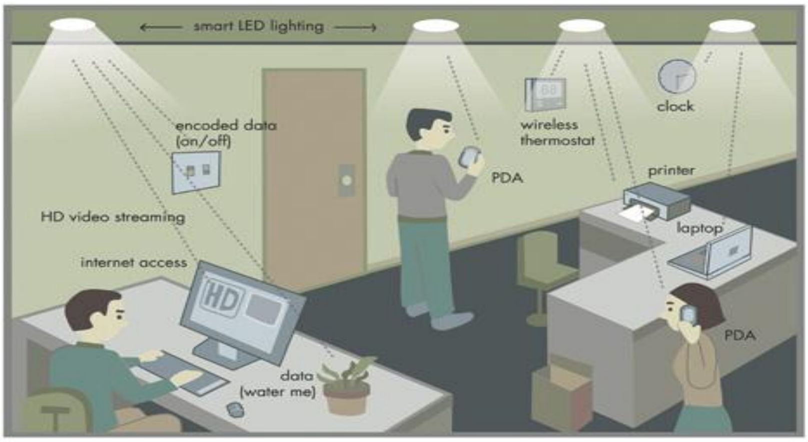

Fig. 1 Boston Smart Lighting office[10].

Transport: LED headlights and taillights are being introduced. Now a days street lamps, signage and traffic signals are also using LEDs. This can be used for vehicle to vehicle and vehicle to roadside communications [11]. Due to this road safety and traffic management will become effective. Communications via street lighting and traffic lights. VLC can be implemented for aircraft traveler lighting to listen music and watch video [12][13], aircraft navigation lights with identification transmission, and car head/tail lamp communications. Figure 2 shows the communication between vehicle to vehicle and vehicle to traffic control infrastructure[14].

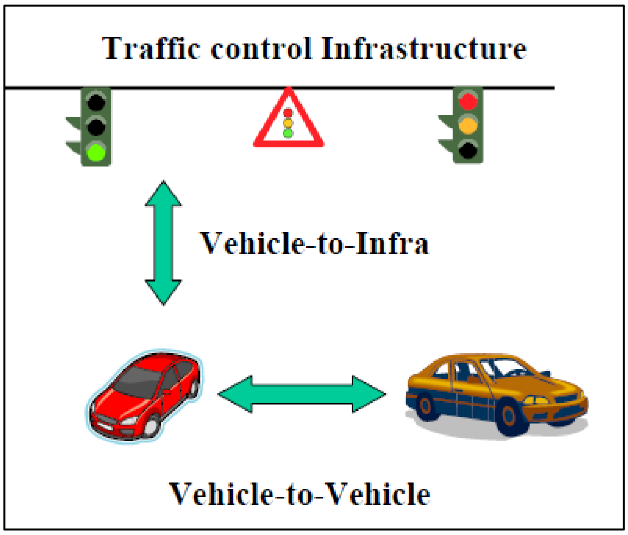

Fig. 2 Application of VLC in Transport [15].

Hospitals: In Hospital medical equipment requires isolation from Electromagnetic Interference (EMI) or Radio Frequency Interference (RFI). VLC does not emit EMI or RFI. So it does not interfere with medical instruments and also it does not interfere with MRI scanners. Hence VLC provides equipment and staff communications with no EMI and RFI problems[12].

Industrial: Industrial and office lighting with inbuilt communications and localization, intrinsically safe communications in areas with flammable materials. VLC provides a safe alternative to EMI from RF communications in environments such as mines and petrochemical plants. Excess capacity demands of Wi-Fi networks can be offloaded to VLC networks[4]. VLC is especially effective on the downlink in the RF congestion area.

Public sector: Transmission of a unique ID is all that is required for basic positioning for providing local information in museums, communications for civil contingencies. Multiple LED light bulbs can be used with relative location for more accurate indoor positioning and navigation[11]. Also in the malls we can provide VLC tags for positioning and localization purpose[16][17].

Homeland security and defense: The VLC technology can be activated in the visible spectrum and by gaining natural advantages of WOC like secure and covert communication. In VLC no Omni

directional emission at very high data rates. Unique VLC positioning and range technology can replace GPS based systems in many places[18].
In commercial market some applications may be similar to some of the Homeland Security applications. The case in which two or more vehicles are required to establish communication and to accurately detect their relative position and distance specially in RF jammed environment. This can be translated to any manned or unmanned moving platforms. The quick deployment and fast communication supplied by VLC makes it the system of choice in a disaster recovery situation. VLC based FSO communication solutions are already in service with several military organizations[19].

IV. VLC CHALLENGES

VLC is still in the early stage that there are many severe problems or limitations needed to be solved.

Line Of Sight (LOS): LOS is a definite advantage because the signal will be stronger. Visible light signals can be reflected but does not penetrate most of objects in our daily life which can be a security advantage and perhaps a coverage disadvantage[20][21]. However, if you look under the table you can still see despite there being no line of sight from light sources. This characteristic can be also considered as a disadvantage that preventing the signal from spreading among multiple rooms. And furthermore, reflection can absorb much energy so that the rate of communication without LOS between the transceivers is greatly limited[22]. Not any optical spread signal under power regulation can be strong enough to let reflected signals still preserve enough power for communication. If light levels are low and VLC receiver can collect photons, it can receive data at a lower data rate. Like radio technology that indirect signals have a lower power and hence the data rate reduces[14][23].

Transmitter Sources: Specialist LEDs with ideal characteristics for VLC would be great. Solid state LED lighting is currently being sold based on its performance for illumination purposes only. Communications performance is not even a secondary consideration so it is entirely impractical to expect the lighting industry to aspect this into designs at this stage. In a practical sense excellent results can be achieved with COTS LED devices. If better devices are available for VLC then great otherwise to implement VLC existing LED devices can be considered[23].

Multipath Distortion: When the transceivers are equipped with wide beam, the copies of the same signal from different paths arrive the destination with different amount of relay, because each path has different length from source to destination[7]. This creates a problem called multipath distortion which can cause Inter Symbol Interference that severely degrades the performance.

Interference from sunlight: This problem is also associated with a wide transmission beams. In visible light, this becomes more critical since the ambient light could be very strong that the resulting SNR is low[7]. The cost will be increased by equipping a receiver good enough for distinguishing such low signal when encountering high signal attenuation. It is relatively simple to eliminate the vast majority of interference from natural and artificial sources using optical filters[23]. After the photo-detector further analogue and digital filtering ensure remaining interference is negligible.

Simplex communication: VLC can be used for transmission of data in either upward or downward direction[11]. The uplink and downlink can be isolated in a number of ways like wavelength, time, code and also by spatial or optical isolation. Due to cost reasons and high bandwidth VLC might be implemented for downlink. Wi-Fi or IR may provide a reliable uplink where congestion is less likely and VLC provides a high capacity uncongested downlink.

Lights on: To use VLC the lights completely needs to be on. The lights are on in the vast majority of industrial, commercial and retail environments when the area is occupied. The lights are usually on for illumination hence VLC transmission power comes free as it is already used. During daylight in domestic environments we do tend to switch off lights. Where the lights would have been off the power required for VLC is not free but the lights only need to be dimmed up to transmit information[24]. The illumination will not be noticed if the illumination level below ambient levels. The power consumed is comparable with the watts/bit for radio transmission and so on aggregate even in domestic environments there is a significant net saving in power[23].

V. NEED OF VLC

The demand of spectrum for communication is increasing at the rate of 108% per year but our present technologies achieves only 12% growth in spectrum per year, so to meet this a complimentary technology to current technology is needed. Our current communication systems are highly inefficient like in RF technology only 5-8% of power is utilized for communication rest all is wastage. Due to very high channel densities conjection problem persists in present communication channels. RF is medically proved to be unfit for humans also it gives rise several neurological diseases and other medical problems too. Now the question comes Why only VLC? The answer is around you that we have numerous amounts of LEDs around us then why to keep their use limited to illumination purpose[26]. LEDs can bring revolution in the way of communication. Some of the facts which can prove this with the growing evolution in optics, semiconductor devices and materials science. The LED technology has been growing in an exponential way. As the 1960's LED's have doubled their

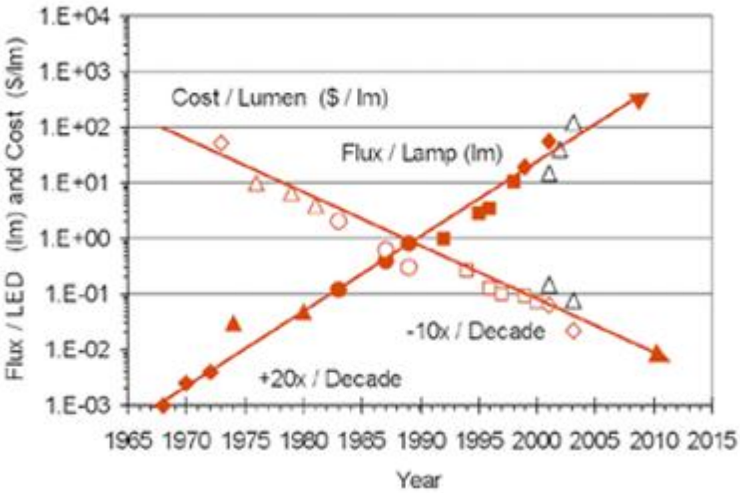

Fig. 3 Haitz graph[25].

light output and power efficiency every 36 months. This behavior is stated by Haitz and known as "Haitz's Law" also it is shown in figure 3. These numbers confirm the penetration of LED's into the market of lighting systems like in automotive applications, in street lighting, indoor lighting, and traffic lighting. LEDs will work as a communication purpose as well as illumination purpose and hence reduces the cost and increases efficiency. The new LEDs coming in the market known as Resonant Cavity (RC) LEDS are very highly efficient. They have very bright light and low power consumption[25].

In table 1 the typical efficiency and lifetime values of common white light sources, are shown, as along with the predicted values of white light LED's around the year 2000.

Table 1. Comparison of different Light sources Efficiency and Lifetime[25].

Lamp Type	Efficiency [lm/W]	Lifetime [h]
100W Incandescent	15	1 000
135W Long Life Incandescent	12	5 000
300W Halogen	24	3 000
50W Compact Halogen	12	2 500
11W Compact Fluorescent	50	10 000
30W Fluorescent	80	20 000
White LED (Year 2000)	20	100 000
White LED (Year 2002)	30	100 000
White LED (Year 2005)	40	100 000
White LED (Year 2010)	50	100 000

Although the values are an optimistic prediction of white light LED's, actual Luxeon Rebel LED's achieve values of 100 lm/W, and a lifetime of 50,000 hours with 70% lumen maintenance, when driven by a current of 700mA. And the state-of-the-art Luxeon K2 LED's can achieve over 200 lm/w, and a lifetime of 50,000 hours with 70% lumen maintenance, when driven by a current of 1A.

VI. COMMUNICATION ARCHITECTURE

The VLC system transmits signals by controlling the ON/OFF repetition of LED or the color of transmitting light. VLC system is a different from RF system. In VLC system LED plays the role of a transmitter and the photo diode plays the role of a receiver [6]. There are two parts of VLC architecture one is a transmitter part and the other one is a receiving part. The sending part can use any kind of LED illumination. The sending part of VLC must have Physical Layer (PHY) & Data Link Layer (DLL) functions for illumination and transmission performance. The receiving Part of VLC can support any kind of Photo Diode with prevention from interference of any other light source. There are a PHY and a Media Access Control (MAC) as a common part of the transmitter and receiver of VLC. PHY has a modulation and a line coding for a wireless communication and VLC MAC has to support different Applications[26]. The OSI reference model of VLC system is illustrated in Figure 4. In this PHY and DLL plays main important role in communication.

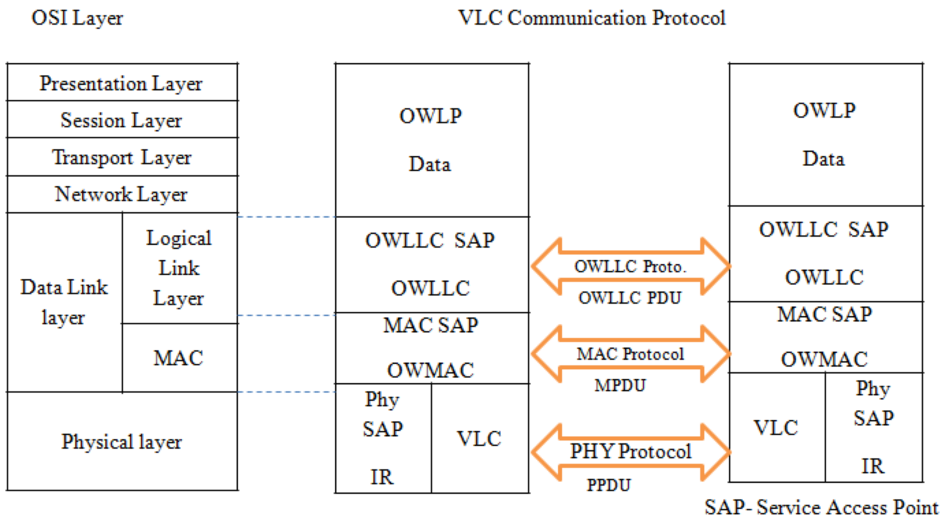

Fig. 4 OSI reference model of VLC Architecture [27].

The physical layer

The PHY defines the electrical and hardware specifications for devices. Exactly it defines the relationship between a device and a physical channel. One device transmits information to the channel, and another device receives data from channel based on the PHY. IEEE 802.15.7 specification defines 7 colors channel for physical layer in VLC. The received power from the color channel band will affect directly on demodulation of information. The received powers of blue, green and red color channels are not constant. This variation affects the performance of the system even though the receiver expects same performance for each color of the channel. Signal to Noise Ratio (SNR) is directly proportional to the square of instantaneous received power. SNR deviation affects the data rate of the VLC system. In VLC SNR depends upon multipath fading, inter symbol interference (ISI), ambient light and other noise sources[6][28]. The PHY modulation scheme of VLC can make light flickering. The light flicker having harmful health impacts on humans and animals. A light flicker is an impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time[29]. Critical Fusion Frequency (CFF) is a frequency at which an intermittent light stimulus appears to be completely steady to the observer. A light flicker causes harmful health impacts such as Visual discomfort, Eyestrain, and Headache. For low-bit-rate transmission, the modulation frequency of VLC must be higher than CFF threshold. The

CFF threshold is minimum 200 Hz (= 5ms) and brightness of each Maximum Flickering Time Period (MFTP) must be all equal. In PHY to achieve full duplex communication it requires a separate uplink and downlink. VLC link mainly used for downlink and for uplink IR or RF is preferred. The communication takes place in terms of packets in the PHY. The Synchronization Header (SHR), PHY Header (PHR), and PHY Service Data Unit (PSDU) together form the PHY packet which is known as a Physical Protocol Data Unit (PPDU)[26].

Several modulation methods are used in high data rate PHY such as Color Code Modulation (CCM), High Hamming Weight code (HHW), On Off Keying (OOK) and VPPM (Variable PPM)[5][7][30]. An LED light flicker due to VLC modulation techniques is not good for eye safety. LED flicker either should be eliminated in VLC for illumination or no one use a VLC as an illumination[31]. By using dimming scheme LED illumination can control brightness[32]. The dimming function is a compulsory for LED illumination[33]. There is need of modulation to support the dimming control function of LED light with full brightness for VLC and illumination. Full brightness is a primary function of LED illumination. A modulation of VLC might be decreasing the brightness of LED illumination[34].

Three physical layer communication options are currently specified as per system requirement.

PHY I: It is designed for low data rate in the range 12 to 267 kbit/s and for outdoor applications. Convolutional and Reed Solomen codes can be used for forward error correction and OOK or VPPM are used for modulation.

PHY II: It is designed for moderate data rates in the range 1.25 to 96 Mbit/s and for indoor applications. Reed Solomen codes can be used for forward error correction and OOK or VPPM are used for modulation[33]. To achieve 96 Mbit/s data rate an optical clock rate of 120 MHz is required and most of the shelf optical devices will not support. A data rate of 9.6 Mbit/s can be achieved by using the most realistic clock rate of 15 MHz.

PHY III: It is designed for data rates in the range 12 to 96 Mbit/s and for applications in which RGB sources and detectors are used. Reed Solomen codes can be used for forward error correction and this time CSK with 4, 8 or 16 color constellations are used[23].

The Data Link Layer

The second lowest layer in the OSI Reference Model is the Data Link Layer (DLL). The set of devices connected at the DLL is commonly considered a simple network, as opposed to an internetwork. The DLL is divided into two sub-layers as an Optical Wireless LLC (OWLLC) and Optical Wireless MAC (OWMAC). This split is based on the architecture used in the IEEE 802.15.7 Project. By separating OWLLC and OWMAC functions interoperability of different network technologies is made easier.

Optical Wireless Logical Link Control (OWLLC): OWLLC as a Logical Link Control (LLC) refers to the functions required for the establishment and control of logical links between local devices on a network. It provides services to the Network Layer above it and hides the rest of the details of the DLL to allow different technologies to work seamlessly with the higher layers. A device shall send association frames to unicast addresses. The ACK acknowledgment policy at the OWMAC sublayer to send association frames shall use by a device. Retransmition of any association frame for which an ACK frame was not received. The OWLLC protocol handles the OWLLC frame format, attribute fields and functions.

Optical Wireless Media Access Control (OWMAC): This refers to the procedures used by devices to control access to the network medium. The OWMAC data communication protocol sublayer provides addressing and channel access control mechanisms that make it possible for several terminals or devices. The hardware that implements the OWMAC is referred to as a Medium Access Controller. This channel may provide half duplex, full duplex or broadcast communication service. The OWMAC sub layer handles all access to the physical radio channel. It is responsible for the tasks as a generating network beacons for coordinator, supporting PAN association and disassociation, synchronizing to network beacons, supporting visibility and dimming, flicker removal scheme, full brightness scheme, supporting signboard for broadcasting, supporting color packets for link establishment and packet error identification, supporting device security, and providing a reliable link between two peer OWMAC entities. The OWMAC sublayer requires the following features provided by the PHY as a frame transmission, frame reception, PLCP header error indication or correction for both PHY and OWMAC header structures, clear channel assessment for estimation of medium activity, the PHY preamble, the PLCP header including MAC and PHY headers and is protected by a 16 octet Reed Solomon error correction code and the frame Payload is followed by its frame check sequence (FCS).

The OWMAC service is communication between cooperating devices within optical range on a single channel using the PHY. Multi sector transmission, a distributed reservation based channel access mechanism and a synchronization facility for coordinated applications is provided by OWMAC. The OWMAC sublayer in turn relies on the service provided by the PHY layer via the PHY Service Access Point (PHY SAP). The OWMAC protocol applies between peer OWMAC entities and the OWLLC protocol applies between peer OWLLC entities. All devices provide all required OWMAC functions and optional functions as determined by the application. The architecture of this OWMAC service is fully distributed. Coordination of devices among the optical range is achieved by the exchange of beacon frames. The periodic beacon broadcast permits device detection, supports dynamic system association, and gives support to mobility. The basic timing for the system and carry reservation and programing information for accessing the channel is provided by beacons. Data is passed between the OWMAC entity and its client in MAC Service Data Units (MSDUs). It is transported between devices as MAC Payload Data Units (MPDU) data frames. To reduce the frame error rate of an insignificant link, data frames are fragmented and reassembled. Fragments are numbered with an MSDU sequence number and a fragment number.

The IEEE 802.15.7 standard provides a single MAC that supports Peer to Peer (P2P), VLAN, IB, VB and visibility modes for VLC communication. Full duplex, half duplex and broadcasting capabilities can be provided with a single OWMAC frame structure. It is required to support all of these different modes into a single integrated frame structure with low complication. Due to this devices such as mobile phones can be built to support multiple modes with a single common OWMAC protocol for area, power and performance. With such an integrated solution, front end optical light source like LEDs or laser diodes (LD) and drivers, the receiving photodiodes, Trans-Impedance Amplifiers (TIA) and parts of the PHY and OWMAC protocols can be shared for multiple modes while simultaneously making it possible to make a single low complexity device that supports all these modes.

VII. FUTURE WORK

VLC is a simplex communication and also it having major research challenge of LOS. In future work VLC be intended to support full duplex communication and overcome over LOS challenge. The protocol should be designed to solve the issue of LOS in VLC and enable the users to fully utilize the capacity provided by access point and user devices.

VIII. CONCLUSION

We presented the concept of VLC in which communication takes place by visible light signal. There are existing applications of VLC, such as domestic and transport. We explained the benefits of VLC over current RF solutions including ability, efficiency, security and safety. These benefits enable a new and wider range of VLC applications, from hospital, where RF signals EMI could impede MRI scanner or are unsightly, to military applications such as homeland security, where two or more vehicles are required to establish communication and to accurately detect their relative position and distance specially in RF jammed environment. This can be translated to any manned or unmanned moving platforms. VLC is in the early stage of wireless communication which poses several research challenges. We explained that the condition of the VLC channel is dependent on the properties of the visible light, particularly the color pattern. Additionally, on low frequencies which are able to flicker the light source so minimum CFF is declared. We also presented structure of each layer of the protocol stack for VLC.

REFERENCES

[1] Mohsen Kavehrad, "Sustainable Energy-Efficient Wireless Applications Using Light", IEEE Communications Magazine, December 2010.
[2] Tzu-Ming Lin, "Visible Light Communication (VLC) Sustainable Energy-Efficient Wireless Applications Using Light", *IEEE Communication Magazine*, Vol: 48, No.12, pp: 66-73, 2010.
[3] Cheng-Chun Chang, Yuan-Jun Su, Umpei Kurokawa, and Byung Il Choi, "Interference Rejection Using Filter-Based Sensor Array in VLC Systems", *IEEE Sensors Journal*, Vol. 12, No. 5, pp: 1025-1032, 2012.
[4] Pure VLC, "Visible Light Communication: An introductory guide", [online] www.purevlc.net, 2012.
[5] Navin Kumar, Nuno Lourenço, Michal Spiez and Rui L. Aguiar, "Visible Light Communication Systems Conception and VIDAS," IETE Technical Review, vol. 25, no. 6, pp. 359-367, Nov-Dec 2008.
[6] Nam-Tuan Le and Yeong Min Jang, "Virtual Cognitive MAC for Visible Light Communication System", *International Journal of Smart Home*, Vol. 6, No. 2, pp: 95-100, 2012.
[7] Chaturi Singh, Joseph John, Y.N.Singh, K.K.Tripathi, "A Review on Indoor Optical Wireless Systems", *IETE Technical* Review, Vol.12, No.2, pp:171-186, 2004.
[8] H. L. Minh, D. O'Brien, G. Faulkner, L. Zeng, K. Lee, D. Jung, and Y. Oh, "High-speed visible light communications using multiple-resonant equalization", *IEEE Photonic Technology Letters*, vol. 20, 2008.
[9] Talha A. Khan, M. Tahir and Ahmad Usman, "Visible Light Communication using Wavelength Division Multiplexing for Smart Spaces", *IEEE Consumer Communications and Networking Conference (CCNC)*, pp: 230-234 2012.
[10] Thomas Little, "Smart light for Ubiquitions communications", 2009
[11] D. O'Brien, H. L. Minh, L. Zeng, G. Faulkner, K. Lee, D. Jung, Y. Oh, and E. T. Won, "Indoor visible light communications: Challenges and prospects", *Proceedings SPIE*, vol. 7091, 2008.
[12] Birendra Ghimire and Harald Haas, "Self-organising interference coordination in optical wireless networks", *EURASIP Journal on Wireless Communications and Networking*, 2012.
[13] Hartmann and M.Pez, "High Throughput Free Space Optical Communication Using White Led Lighting Equipment", *IEEE Avionics, Fiber-Optics and Phototonics Technology Conference*, Pages: 78-79 2009.
[14] Joint Industry and Traffic Engineering Council Committee, "Vehicle Traffic Control Signal Heads- Light Emitting Diode (LED) Circular Signal Supplement," JITECC, 2005.
[15] IEEE 802.15 working group for WPAN's, "Visible Light Communications Tutorials", 2008.
[16] Soo-Yong Jung, Swook Hann, and Chang-Soo Park, "TDOA-Based Optical Wireless Indoor Localization Using LED Ceiling Lamps", *IEEE Transactions on Consumer Electronics*, Vol. 57, No. 4, pp: 1592-1597, 2011.
[17] IEEE 802.15 LED(Light Emitting Diode) Interest Group (IG-LED)
[18] D-Light [Data-light Project]. www.see.ed.ac.uk/research/1Dcom/d-light.
[19] Supreme Architectures, "VLC Applications", www.supremearchitecture.com
[20] Debbie Kedar and Shlomi Amon, "Non-line-of-sight optical wireless sensor network operating in multi-scattering channel", *Journal Of Applied Optics*, Vol. 45, No. 33, pp: 8454-8461, 2006.
[21] Y. Tanaka, Haruyama, S.and Nakagawa, M, "Wireless optical transmissions with white coloured LED for wireless home links," in *PIMRC, The 11th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, , pp. 1325 – 1329, 2000.
[22] Gerry Melnikov, Guido M. Schuster, and Aggelos K. Katsaggelos, "Shape Coding Using Temporal Correlation and Joint VLC Optimization", *IEEE Transactions on Circuits and Systems For Video Technology*, Vol. 10, No. 5, pp: 744-754, 2000.
[23] VLCC: Visible Light Communication Consortium. [Online]. http://www.vlcc.net., 2008.
[24] T. Borogovac, M. Rahaim, M. Tuganbayeva, and T.D.C. Little, "Lights-off' Visible Light Communications," *Proc. IEEE Globecom 2011 2nd Workshop on Optical Wireless Communications* (OWC 2011), pp. 823-827, Dec. 5-9, 2011.
[25] Haitz R., F. Kish, J. Tsao, J. Nelson, "The Case for a National Research Program on Semiconductor Lighting", *Optoelectronics Industry Development Association (OIDA 1999)*, Washington, Oct. 1999.
[26] IEEE 802.15.7, "VLC PHY/MAC Proposal-Samsung/ETRI", 2009. https://mentor.ieee.org/802.15/dcn/09/15-09-0733-00-0007-vlc-phy-mac-proposal-samsung-etri.pdf
[27] Project OMEGA,"Optical Wireless MAC Specification", www.ict-omega.eu., 2009.
[28] Jupeng Ding, Zhitong Huang, and Yuefeng Ji, "Evolutionary Algorithm Based Power Coverage Optimization for Visible Light Communications", *IEEE Communications Letters*, Vol. 16, No. 4, pp:439-441, 2012.

[29] IEEE 802.15.7 WPAN, "Suggestion for VLC communications", 2010.
[30] Muhammad Tahir, and Abu Bakar Siddique, "Optimal Brightness-Rate Control using VR-MPPM and its Spectral Analysis for VLC System", *IEEE Communications Letters*, Vol.16, No. 7, pp: 1125-1128, 2012.
[31] IEEE 802.15 working group for WPAN's, "IEEE 802.15.7 VLC PHY/MAC specification proposal", 2009.
[32] G. Ntogari, T. Kamalakis, J. W. Walewski, and T. Sphicopoulos, "Combining Illumination Dimming Based on Pulse-Width Modulation with Visible-Light Communications Based on Discrete Multitone", *Journal of Optical Communication and Network*, Vol. 3, No. 1 pp:56-65 2011.
[33] Sridhar Rajagopal, Richard D. Roberts, Sang-Kyu Lim, "IEEE 802.15.7 Visible Light Communication: Modulation Schemes and Dimming Support", *IEEE Communications Magazine*, Vol. 50, Issue: 3, pp**:** 72-82, 2012.
[34] Hany Elgala, Raed Mesleh, Harald Haas, "Indoor Optical Wireless Communication: Potential and State-of-the-Art", *IEEE Communications Magazine*, pp:56-62, 2011.

AUTHORS

Manoj V. Bhalerao has completed his post-graduation in Electronics Engineering from Dr. Babasaheb Ambedkar Marthwada University, Aurangabad, India. He has received B.E. degree in Electronics & Telecommunication Engineering from Pune University. He is currently working with VLC and his main research interests area are in VLC and DSP.

S. S. Sonavane received Ph.D. in 2008 from Indian School of Mines, Dhanbad. He is currently working as Professor and Principal of DYP School of Engineering, Pune. He has published around 18 papers in International and National journals and Conferences. His area of interest is wireless sensor network.

V. Kumar received Ph.D in 1980 and worked as Scientist at CMRI, Dhanbad and Visiting Scientist at CNR, Frascati, Roma, Italy during 1983- 84. He has attended number of International Conferences including conferences held in USA, Portugal, Singapore and Italy. At present, he is Professor in Electronic & Instrumentation Department, ISM University, Dhanbad. He has published over 100-research papers; guided 3-Ph.D. and number of M. Tech students in the areas of Opto-electronic materials and Optical Fiber Sensors.